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THE EFFECT OF INTENSITY OF LIGHT, STATE OF ADAPTATION OF THE EYE, AND SIZE OF PHOTOMETRIC FIELD ON THE VISIBILITY CURVE

A STUDY OF THE PURKINJE PHENOMENON

BY

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PREFACE

The subject of this dissertation was suggested by Professor C. E. Ferree of the Department of Psychology of Bryn Mawr College, and the dissertation was prepared under his direction. The writer wishes to acknowledge her indebtedness to Professor Ferree for the suggestion of the problem and to both Professor Ferree and Dr. Rand for guidance, advice, and assistance throughout the entire period of work. She wishes also to express her appreciation to Dr. Rand for her kindness in making the energy measurements needed in this investigation.

CONTENTS

I. INTRODUCTION

The terms "visibility curve," "visibility function," etc., seem to have been introduced first by Nutting in 1908. The concept of some sort of a mathematical function to express the relation between luminosity and energy throughout the spectrum had, however, been suggested by Goldhammer (1) in 1905. Goldhammer attempted to express the relation mathematically in the following equation: $\frac{F_\lambda}{e_\lambda} = \phi(\lambda)$ where e_λ is the energy, F_λ the brightness, and $\phi(\lambda)$ the visibility at the wave-length λ. The facts of the Purkinje phenomenon, he points out, show that the function $\phi(\lambda)$ must depend upon e. Thus if we choose a given value of e and determine $\phi(\lambda)$, this function will depend upon the value of e chosen. Similarly, if we determine $\phi(\lambda)$ for a constant value of F, the function $\phi(\lambda)$ will not be the same for all values of F.

Although most of those who have since used the term visibility curve or visibility function probably have had in mind some sort of relationship similar to that suggested by Goldhammer, several procedures have been used in the determination of the visibility curve. (1) In some investigations the luminosity curve of an equal energy spectrum has been determined. In this method the number of meter-candles, for example, of light given by a constant amount of energy is measured for various wave-lengths throughout the spectrum. Data obtained by this procedure have been published by Ferree and Rand and by Laurens. The method is equivalent in Goldhammer's nomenclature to a determination of F_λ for a constant value of energy. From the equation we see that in this case $\phi(\lambda)$ is directly proportional to F. Consequently the visibilities for the different wave-lengths are proportional to the meter-candle values for these wave-lengths.

(2) A second method of obtaining the visibility curve has

been to determine at each wave-length the amount of energy necessary to give a certain level of sensation, specified in photometric units. According to Goldhammer's equation this method is equivalent to a determination of e_λ for a constant value of brightness. From the equation we see that in this case values of $\phi(\lambda)$ are proportional to the reciprocals of the energy values. This method of determining visibility data at a constant brightness level, which is known to psychophysicists as the method of equivalents, has been the one most generally employed. It has been used, for example, by Koenig, Houston, Ferree and Rand, Hecht, Ives, Coblentz and Emerson, Laurens, and by Hyde, Forsythe and Cady. The so-called threshold visibility curve is obtained by a modification of this second method. In this case visibility is measured by the reciprocal of the amount of energy required to give a just noticeable sensation. Koenig considers that this is equivalent to the procedure described above, since brightnesses which are just noticeable must, he thinks, be regarded as equal. The just noticeable brightness can therefore be conceived of as a definite sensation level. Threshold visibility determinations have been made by Ebert, Langley, Pflueger, Koenig and Monroe.

(3) Other investigators of the visibility curve have assumed that the Purkinje phenomenon is not present at the high intensities used by them, and have therefore not kept either the energy or the brightness level constant. This procedure has been used by Hyde, Forsythe and Cady and by Gibson and Tyndall. The latter, for example, define visibility at a given wave-length as equal to L/W, where L equals lumens and W equals watts. The procedure is to determine the luminosity and the energy at certain points in a given spectrum. The visibility at each of these points is then obtained by dividing the value in lumens at that wave-length by the value in watts.

(4) Another form of the methods given in (1) and (2) would be to measure the brightness in sensation units instead of photometric units, using the just noticeable difference as the unit of

sensation.[1] Thus in method (1) the number of j.n.d.'s at each point in the spectrum given by the chosen amount of energy would be determined, and the respective visibilities would be rated as proportional to the number of j.n.d.'s obtained in each case. Or, in method (2), the constant brightness level chosen for all wave-lengths would be specified in j.n.d. units. These methods, so far as we know, have never been used.

In the presence of several well sponsored methods, the question naturally arises as to which should be used in determining the visibility function. A question so fundamentally important as this can be discussed here only in a tentative way. For example, (a) the validity of the third procedure, *i.e.*, that used by Hyde *et al.* and by Gibson and Tyndall, depends upon the correctness of their assumption that the relation of the lumen to the watt is a constant for all intensities of a given wave-length. If, however, we exclude data obtained by flicker and other indirect methods of photometry, we find that there is very little evidence to support this assumption; on the contrary, a number of investigators claim that there is an effect of intensity on the visibility curve, although less in amount, at high as well as at low intensities. (b) The first of the methods cited above, namely, the determination of the relative luminosities at the different wave-lengths of an *equal energy* spectrum, does not involve this assumption. This method may undoubtedly be of interest and have decided value in certain practical applications. However, from the point of view of the psychophysicist whose object is to determine the relation between stimulus and response, the method is not satisfactory. The psychophysical problem requires that sensation values be correlated with stimulus values. According to this requirement, F in Goldhammer's equation should be expressed in sensation, not photometric terms. $\phi(\lambda)$ then becomes an expression for the sensitivity at different wave-lengths, where sensitivity may be defined as the ratio of the number of units of sensation to the number

[1] For practical purposes in this discussion all theoretical and systematic doubts will be waived and the just noticeable difference will be regarded as a unit of sensation.

of units of stimulus. (c) The psychophysical requirement that amounts should be specified in sensation terms is satisfied equally well by either of the two remaining methods, *i.e.,* in method (2) equal amounts of sensation are used and in method (4) the amounts of response are rated in terms of just noticeable differences in sensation. There remains then only the question whether the determination at the different points in the spectrum should be made at a constant level of energy or of sensation.

The same question might be raised with regard to the determination of the sensitivity of a physical instrument, *e.g.,* a galvanometer. Should the sensitivity be rated in terms of the amount of current necessary to give a unit of deflection, or in terms of the amount of deflection produced by a unit of current? If the deflection is proportional to the current throughout the intensity scale, one form of specification can easily be deduced from the other; moreover, the sensitivity need be determined at only one point in the scale or for only one amount of current. The situation is not so simple, however, in the case of the eye. To make the situation more analogous to that of the eye, let us assume as a hypothetical case an alternating current galvanometer whose sensitivity varies with the frequency of the alternation, and whose sensitivity for a given frequency varies throughout the intensity scale. In such a case we might determine the sensitivity to a series of frequencies, either for a certain amount of current or for a certain amount of deflection. This would give us information, however, for only one point in the scale or for only one value of current. To get a complete calibration of the scale for any one frequency we should have to determine either the deflection for a series of values of current or the amounts of current necessary to give a series of deflections. From these data a curve could be plotted for the frequency used from which the value of current corresponding to any deflection or, conversely, the deflection produced by any amount of current could be obtained.

Similarly in case of the eye where the sensitivity is not constant for any wave-length but changes irregularly with change of

intensity of the stimulus, calibration curves could be obtained for each wave-length. Thus if we were to determine the energy corresponding to the j.n.d.'s of sensation given by the different wave-lengths of the spectrum for the desired range of intensity, we should have data which could be plotted (a) to show the relation of the eye's response to intensity for the different wave-lengths at any level of energy or at any level of sensation, and (b) to give for any particular wave-length an empirically determined curve showing the relation between stimulus and sensation. Sensitivities could then be rated as directly proportional to the number of j.n.d.'s given by equal energies of the different wave-lengths of light and the assumption involved in the usual method of making the comparison would be avoided. That is, the amounts of response for equal amounts of stimulus are measured directly. They need not be deduced from an assumed law of relation. They cannot be deduced, for example, from the amounts of energy required to give equal responses unless the relation between stimulus and response is known. The usual method of making the deduction assumes a simple proportionality, an assumption which is of course not correct.

A great deal of the work that has been done thus far on relative visibility has taken the form of determining a curve for the average eye. Many practical applications are planned for such a curve in adapting light to the use of the eye. This, we believe, is premature until a better knowledge is had of the factors which influence the results of visibility determinations. The present study has been planned, therefore, for the purpose of extending this knowledge; *i.e.*, an investigation has been made of the effect of three important factors: intensity of light, state of adaptation of the eye, and size of the photometric field on the shape and position of the visibility curve.

The method of equivalents has been selected for making this study. This selection has been made for the following reasons: (1) Visibility data have a practical use which is probably more important than their psychophysical bearing, namely, they express the relation between photometric and radiometric ratings of

intensity of light for the different wave-lengths of the spectrum. For this purpose the method is correct. (2) The alternative procedure, the determination of the number of j.n.d.'s for equal amounts of energy, which is perhaps more nearly correct for use in the psychophysical problem of comparing numerically sensitivities at different points in the spectrum, would involve so many determinations of the just noticeable difference as to be entirely infeasible for a study of the range here contemplated, or for a greater part of the practical purposes for which visibility determinations are needed. And (3) the method of equivalents is the one most frequently used. This gives a special practical importance to studies leading to a knowledge and control of the variable factors which influence the determinations by this method.

Before proceeding to the presentation of the experimental work conducted in the study of these factors, a more detailed account will be given of the methods used and the results obtained in previous studies of the visibility curve.

II. HISTORICAL AND CRITICAL

In discussing the previous investigations relating to this study, we shall deviate somewhat from the chronological sequence in order to be able to consider them under the following headings:

(A) Threshold curves of sensitivity and visibility curves at low intensities. Under this heading a survey will be given of the attempts that have been made to determine the eye's selectiveness of response at the threshold and at very low intensities of light. (B) The effect of change of intensity of light on the visibility curve—the Purkinje phenomenon. In this section the investigations that have been made to determine the change in the selectiveness of response to wave-length with change of intensity of light will be discussed. These investigations include (a) direct studies of the Purkinje phenomenon, and (b) visibility and luminosity measurements at different levels of intensity. (C) The visibility curve at high intensities. In these studies the determinations have usually been made at a single level of intensity. (D) The effect of state of adaptation on the visibility curve. No investigations have been made to determine this effect directly. Scattered determinations have been made, however, under different conditions of adaptation, from which rough comparisons may be made. (E) The effect of size of photometric field on the visibility curve. Under this heading will be included studies made to determine (a) whether the Purkinje phenomenon occurs in the fovea and (b) visibility and luminosity curves for different sizes of photometric field.

A. Threshold Curves of Sensitivity and Visibility Curves at Low Intensities

The first attempts at a quantitative determination of the selectiveness of the achromatic response of the eye to wave-length were made in 1888. Previous to that time several investigations had been made of the relative luminosities of different parts of the

spectrum. For example, in 1817, Fraunhofer (2) determined the luminosity curve of the spectrum in order to obtain data to be used in the designing of achromatic lenses. Later Helmholtz (3) and Dobrowolsky (4) also determined luminosity curves. At this time no apparatus had been perfected sufficiently sensitive to measure the distribution of energy in the spectrum. Consequently, since the luminosity at the different points in the spectrum depends both on the energy of the light and the sensitivity of the eye, no quantitative estimate of the selectiveness of response of the eye to wave-length can be obtained from these determinations of relative luminosity. In 1883, however, Langley (5) succeeded in measuring the distribution of energy in the spectrum of sunlight by means of a bolometer. This achievement was soon followed by a number of investigations of the character of the eye's response.

In 1887, Stenger (6) on the basis of Langley's results showed that the eye must be selectively sensitive to light of different wave-lengths. He pointed out that when the spectrum of sunlight is gradually reduced in intensity, it finally shrinks to a small band in the green. The energy in such a spectrum, however, according to Langley's measurements, reaches its maximum in the infra-red and decreases from the red end of the visible spectrum toward the violet. Consequently Stenger concluded that the eye must be more sensitive to green than to red. In the following year (1888) both Ebert (7) and Langley (8) published quantitative data on the relative achromatic sensitivity of the eye at different points in the spectrum.

Ebert investigated the threshold sensitivity of the eye for five different points of the spectrum. His purpose was to show that the selectiveness of response of the eye would affect the apparent character of the spectra produced by faint sources. Most gaseous nebulae, for example, appear to the eye to have very simple spectra, consisting of only three lines located in the blue and the blue-green. This is just what would be expected, Ebert thought, if the eye were more sensitive in this region than any other. Steinheil's apparatus was used to obtain the spectrum light. The

observer viewed the prism surface by placing his eye at the analyzing slit. No data as to the size of the stimulus field are given. A sheet of illuminated oiled paper served as the source of light, an image of which was formed on the collimator slit by means of a lens. A circular diaphragm was placed between this lens and the illuminated surface. Known variations in intensity were made by moving this diaphragm toward or away from the lens and so varying the effective aperture of the latter. At each of the five points of the spectrum the amount of reduction necessary to give a just noticeable achromatic sensation was determined. The eyes of the observers were dark-adapted.

The energy content of the spectrum light was determined indirectly as follows: Meyer (9) had previously made a spectrophotometric comparison of the spectra obtained from gaslight and sunlight. From Langley's measurements of energy in the spectrum of sunlight and from Meyer's spectrophotometric data on the relative energies of the two spectra, Ebert calculated the energy in the spectrum of the gaslight at each of the five groups of wave-lengths used by him.[1]

Langley's investigation, (8) published in the same year as that of Ebert, was made with the spectrum of sunlight. The original energy measurements made in 1884 were found to agree with a supplementary series made in 1888. In the latter series the same prism was used as in the visual measurements. It is not stated, however, that the remainder of the spectroscopic equipment was the same. In making the visual determinations the different wave-lengths were made photometrically equal by the visual acuity

[1] The energy values determined by this indirect procedure are obviously liable to several sources of error:

(a) The gas flame used by Meyer may have differed in its energy distribution from that used by Ebert.

(b) Meyer's spectrophotometric determinations were made several years before Langley's energy measurements. It could scarcely be expected therefore, that the atmospheric conditions were the same for the two determinations. Changes in the atmospheric conditions would affect the distribution of energy in the sun's spectrum.

(c) The spectroscopic apparatus used by Meyer and Ebert were different. There is no guarantee, therefore, that the transmission of the two instruments was the same, that the same width of spectrum band was obtained, or that the same degree of purity of light was secured.

method; *i.e.,* the intensity of each of the lights was adjusted to give the same visual acuity. Assuming that the energy content of these lights was known from the measurements made with the bolometer, and knowing the amounts of reduction that were produced, it was possible to calculate the amount of energy at the various points in the spectrum that was necessary to give the chosen standard of acuity. Curves were then plotted with the wave-lengths as abscissae and the reciprocals of these energy values as ordinates. No mention is made of the state of adaptation of the observer's eye. It seems probable, however, from the arrangement of the apparatus, that the room in which the observations were made was fairly dark. Consequently it seems safe to assume the observer's eye was fairly well dark-adapted. No data are given as to the visual angle subtended by the photometric field.

Langley considered that theoretically the proper procedure would have been to use an equal energy spectrum and to measure the different " visual effects " of this amount of energy at the different wave-lengths. He states, however, that " for the comparatively feeble lights employed it is nearly immaterial within the limits of experiment what unit of energy we take "; and later says: " Since the thermal and luminous effects vary proportionately in the same ray, it is to be observed that the values in Table I furnish for each wave-length a divisor which gives not only the heat but the brightness which would have been observed had the prism dispersed the energy which fell on it in such a way that the same amount of energy fell in one part of the spectrum as in another." Langley gives, however, no experimental evidence in support of this assumption that for low intensities the luminous effect at a given wave-length is proportional to the energy. Two false assumptions in fact are involved in his statement: (a) the subjective brightness or luminous effect is proportional to the thermal effect; and (b) acuity is proportional to the subjective brightness. Langley also gives data on the " minimum visible," *i.e.,* the amount of light needed to give the threshold sensation at four points in the spectrum, namely, 400, 550, 650 and 750 mμ.

Koenig, (10) the next to take up the problem, published in 1891 an extensive investigation of the luminosity of the spectrum at a number of different intensities ranging from very high to threshold values. This work will be discussed in detail in a later section. We shall consider here only the data on the visibility of normal subjects at low intensities for comparison with the other investigations in this section. The observations were made under dark adaptation. The size of the photometric field was not specified. Koenig's energy values, like Ebert's, were determined indirectly. The data used in making the calculation were (1) Langley's bolometric measurements of the spectrum of sunlight and (2) a spectrophotometric comparison of gaslight and sunlight made previously by Koenig and Dieterici. (11) The results of Koenig's study averaged for his two normal observers (Koenig and Koettgen) and recalculated by the writer to give the maximum visibility a value of 100 are given in Table I and Fig. 1. Table I and Fig. 1 also contain data for one of the observers (Koenig) which have been corrected by Nutting (12) to accord with more recent measurements of the distribution of energy in the spectrum of a gas flame. The effective intensity of the light employed cannot be stated directly. It was the photometric equivalent of that obtained by viewing a magnesium oxide surface illuminated by 0.0045 m.c. through an artificial pupil of 1 sq. mm.

Pflueger, (13) in 1902, was the next to publish data on threshold visibility. He undertook to make a more satisfactory determination than the previous ones (a) by using a greater number of observers, (b) by making readings at a greater number of wavelengths, and (c) by making *direct* measurements of the relative energies in the different parts of the spectrum. A Nernst lamp was used as source, the light from which was diffused by a milk glass plate placed over the collimator slit. The energy determinations were made by means of a Rubens thermopile and a du Bois-Rubens galvanometer. In the visual determinations the eye was placed at the ocular slit. This slit was reduced to 0.75 mm. in height for the visual measurements and thus served as an artificial pupil. To make the threshold determinations easier, a screen of

black paper containing a central aperture was placed over the face of the prism. The purpose of this was to provide a black field to serve as a standard for the judgment of the achromatic threshold. The stimulus field subtended a visual angle of approximately 12 deg. Reductions in the intensity of the spectrum light were made in three ways: (1) by moving the Nernst filament further from the slit, (2) by interposing rotating sectored discs in the path of the light, and (3) by varying the width of the collimator slit. The last method was used only for finer changes in order that the composition of the light might be affected as little as possible by changes in the width of the slit. The first of these methods of reduction, it may be noted, can be considered as the correct procedure only on the assumption that milk glass is a perfect diffuser. No mention is made as to the precautions taken to shield the eyes of the observers from stray light. These precautions are of prime importance in making threshold determinations.

Ten observers were used, each of whom made from one to six separate sets of measurements. The curve for one observer was determined at nineteen points in the spectrum. In most cases, however, determinations at a number of these points were omitted. Twenty minutes was found to be sufficient to insure dark adaptation. Determinations were made only in the direction of decreasing energy, because it was found that in the reverse procedure the observers did not always take the proper fixation. This condition gave, of course, the maximum effect of what is known as the error of expectation.

The sensitivity curves obtained by Pflueger are very irregular in shape and show, moreover, a very large diurnal variation. Many of the curves show a tendency toward a secondary maximum. Because of their irregularity, Pflueger did not consider it feasible to average the different curves. He describes their general characteristics as follows: " Die absolute und die relative Farbenempfindlichkeit des Auges, gemessen bei den Schwellenwerten des Reisempfindung, ist grossen individuellen Verschiedenheiten, und bei demselben Auge, grossem Wechsel unterworfen.

Die Empfindlichkeit ist grössten fur den Spectralbereich $\lambda = 495$ $m\mu$ bis $\lambda = 525$ $m\mu$. Sie kann fur $\lambda = 717$ $m\mu$ den 33000 ten für $\lambda = 413$ $m\mu$ den 60 ten Teil des Wertes im Grün betragen."

In 1913 Houston (14) published data on the average visibility of 52 observers of normal color vision. The determinations were made at two levels of intensity, 0.5 and 0.00167 m.c., respectively. The photometric field consisted of an oblong strip illuminated by spectrum light, and bounded on either side by colorless comparison surfaces. The strip subtended a visual angle of 9 deg. in height and 1 deg. in breadth. It was illuminated by light from a Hilger constant deviation spectroscope. The comparison surfaces were illuminated as follows: The light from a 16 c.p. carbon lamp was allowed to fall upon two white reflecting surfaces. By means of two mirrors and two totally reflecting prisms, the light from these surfaces was reflected into the objective tube of the instrument and thence to the eye. The photometric field was viewed through a black tube, so that the conditions of the surrounding field might be similar to those used in ordinary photometric work. No statement is made as to the state of adaptation of the observers' eyes. It seems safe to assume, however, that they were fairly well dark-adapted, at least for the greater part of the time. A direct measurement of the energy of the lights employed was not made. The energy distribution of the spectrum of the carbon lamp was determined, however, by a spectrophotometric comparison with a Hefner lamp, the energy distribution of which was known.

Variations in the intensity of the spectrum light were produced by using different widths of collimator slit.[1] The usual procedure in such cases is first to set the spectroscope so that the standard field is illuminated with light from the desired region of the spectrum, and then to vary the width of the collimator slit until a photometric match is obtained. Houston, however, used a somewhat different method. In this method the width of the slit was set at a certain predetermined value, and the wave-length

[1] This method is open to criticism because the purity of the light of the spectrum varies with the width of the slit.

drum of the spectroscope was rotated until a region of the spectrum was found which gave a photometric match with the comparison field. This procedure was repeated for three other values of slit-width. The method by which observations were taken is described by Houston as follows: "The slit was then set in succession at four standard widths and for each of these widths on each side of the brightest part of the spectrum, wave-lengths were sought for which the intensity of the spectrum matched the intensity of the white surfaces. Thus eight points were obtained on the luminosity curve. Then for a wave-length midway between the middle points already obtained the width of the slit was diminished until the intensities matched and an additional point thus obtained." The luminosity curves of all the observers were averaged to give a single curve for each of the two intensities. Since a predetermined series of wave-lengths was not used in the photometric determinations made by each of the fifty-two observers, it was necessary to resort to interpolation both in the luminosity and energy curves, in order to obtain the data needed for calculating the average visibility curve.

For the intensity of 0.5 m.c. the point of maximum visibility of this average curve occurs at 502 mμ; for 0.00167 m.c. at 466 mμ. The tabular data from which these curves are plotted are not given. In order to obtain these values for the purpose of plotting a curve which can be compared with the results of other investigators, the ordinates of Houston's curves were read from his graphs and recalculated to give the maximum visibility a value of 100. Only four wave-lengths in addition to that at which the maximum visibility occurs could be calculated in this way, because the abscissae of Houston's curves represent prismatic, not normal dispersion of the spectrum. Since wave-length in this irregular spacing was specified at only four points, interpolation was not possible. The data obtained are given in Table I and Fig. 1.

In 1922, Hecht and Williams (15) made a study of the visibility curve for low intensity, in which the energy measurements were made directly and a large number of observers were used. They

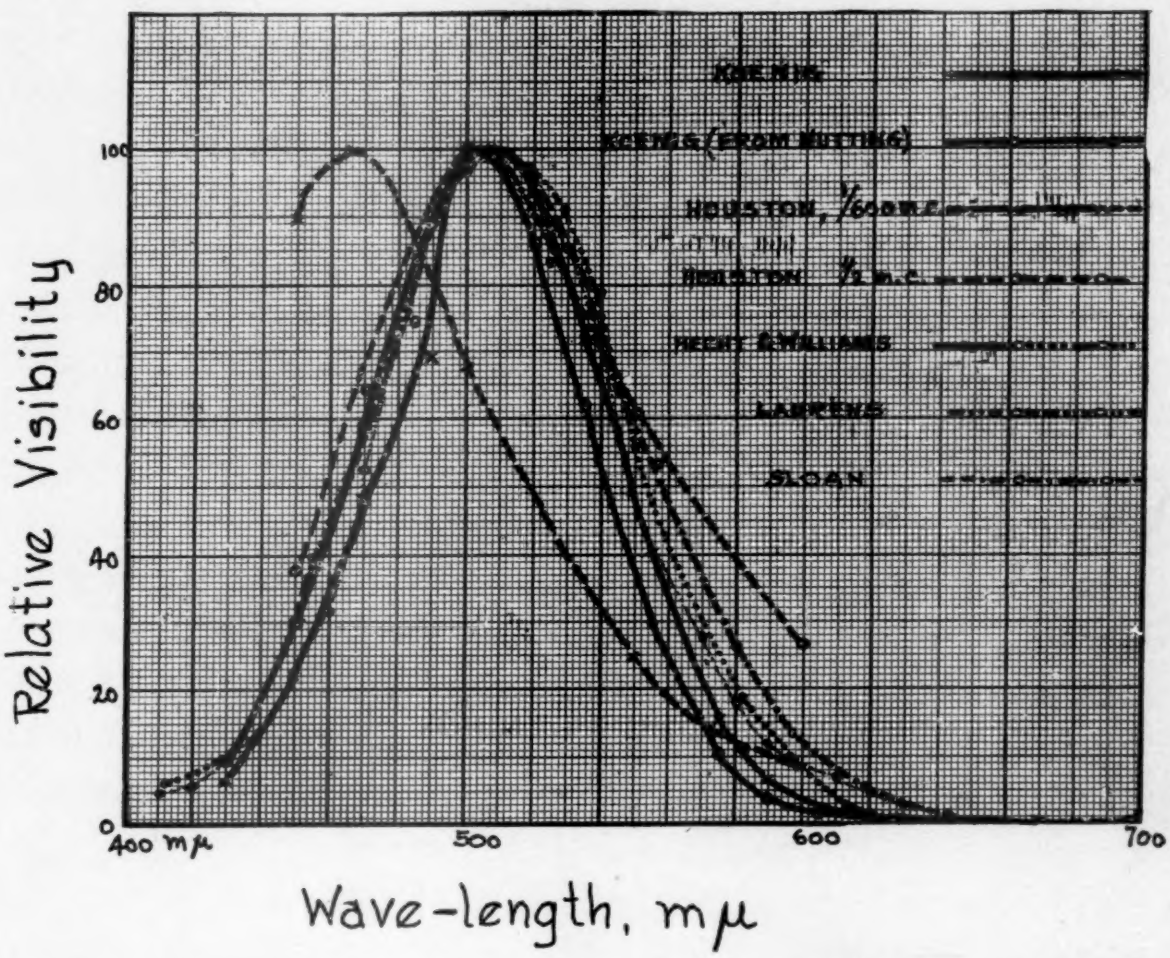


FIG. 1. Showing the visibility curves of spectrum lights as determined by various investigators for dark adaptation and low intensities of light; size of field ranging from 2 to 22 deg.

TABLE I

TABLE I

Showing the relative visibilities[1] of spectrum lights as determined by various investigators for dark adaptation and low intensities of light; size of field ranging from 2 to 22 degrees.

Koenig			Houston			Hecht and Williams		Laurens		Sloan	
Size of Field not specified			Size of Field 9° by 1°			Size of Field 22°		Size of Field 2°		Size of Field 4° 49′	
Wave-length	Visibility 2 observers data from Koenig	Visibility 1 observer data from Nutting	Wave-length	Visibility 0.00166 m.c.	Visibility 0.5 m.c.	Wave-length	Visibility	Wave-length	Visibility	Wave-length	Visibility
430 mμ	6.4	9.3	450 mμ	89.6	37.7	412 mμ	6.32	410 mμ	4.9	454 mμ	36.4
450	22.0	30.0	466	100.0		455	39.95	420	6.0	470	64.1
470	48.0	59.0	500	67.3	100.0	486	83.40	430	9.2	485	74.2
490	69.0	89.0	502		100.0	496	93.90	440	14.3	502.5	100.0
505	100.0	100.0	550	24.8	60.3	507	99.35	450	22.3	552.5	83.2
520	93.0	86.0	600	8.15	26.4	518	97.30	460	31.5	540	73.5
535	71.5	62.0				529	91.10	470	52.1	557	53.15
555	40.5	30.0				540	78.78	480	72.6	580	26.2
575	15.5	10.2				550	55.60	490	88.1	59.75	13.4
590	6.6	3.4				582	17.78	500	96.8	619	5.81
605	2.3	1.2				613	2.72	502.5	98.0	643	1.33
625	0.68	0.4				666	0.181	505	99.1	697	0.118
650	0.145	0.00						507.5	100.0		
670	0.044	0.00						510	100.0		
								512.5	98.7		
								515	97.5		
								520	93.5		
								530	85.2		
								540	66.1		
								550	47.7		
								560	34.9		
								570	27.8		
								580	17.6		
								590	12.0		
								600	8.1		
								610	7.0		
								620	4.5		
								630	2.8		
								640	1.0		

[1] In this and the following tables visibility is taken as the reciprocal of the energy of the light required to match the photometric standard at the various intensities. For convenience of comparison the reciprocals have been reduced in every case to a scale in which 100 has been chosen to represent the maximum value.

considered unsatisfactory the only previous data which fulfilled these two requirements, namely, that of Pflueger, because of the irregularity of the results obtained. Hecht and Williams, in preliminary work, also found difficulty in getting consistent results by the threshold method. By using the equality of brightness method, however, they found no difficulty in getting regular and reproducible results. The intensity used was below the chromatic threshold, consequently the difficulties of heterochromatic photometry were avoided.

A constant deviation spectroscope was used to furnish the spectrum light. Relative energy measurements were made at the analyzing slit by means of a Hitchens thermopile and a Broca galvanometer. The constant comparison field consisted of a layer of radium paint, whose brightness was 2.7 times the intensity required for the threshold in dark adaptation. Such a comparison field, the authors say, gives a constant illumination if not exposed to light. The whole stimulus field subtended a visual angle of 22 deg. Two neutral filters and a pair of Nicol prisms were used to reduce the spectrum light to match the comparison field. Determinations were made for forty-eight observers at twelve points in the spectrum. The observers were dark-adapted for thirty minutes before readings were taken. The average visibility curve of the forty-eight observers is shown in Fig. 1. The data are given in Table I. The maximum of the curve, it will be seen, is at 511 mμ. If shifted 48 mμ toward the red, the entire curve, as Hecht shows, coincides very closely with the curve for high intensities determined by Hyde, Forsythe and Cady. The results obtained by these writers will be considered later.

Laurens (16) in 1924 determined visibility curves by both the flicker and equality of brightness methods at several intensities. His work for only the lowest of these intensities will be considered here; the discussion of the remainder will be deferred to a later section. This lowest intensity is specified as 0.2 m.c. It was probably reduced, however, as will be shown later (p. 27), to some unknown effective value by an artificial pupil having an

area of 1.25 sq. mm. The eyes of the observers were dark-adapted, and a field size of 2 deg. was used. A fixation point was obtained by the method of Abney and Watson as follows: A glass rod about one millimeter in diameter was ground to a point at one end at an angle of 45 deg. Red light which passed down the rod was diffused at this point, to give a small dim source. The averaged data for the two observers are given in Table I. A curve which has been plotted from these data is shown in Fig. 1.

The most recent data on visibility at low intensity were obtained by Monroe, (17) who determined the achromatic threshold under dark adaptation at seven points in the spectrum. She found no difficulty in securing satisfactory reproducibility of result by the threshold method when adequate precautions were taken for the control of variable factors. Threshold determinations were made for twenty-one observers at the following points in the spectrum: 655, 616, 580, 553, 522, 489, and 463 $m\mu$. For nine of the observers the point of maximum sensitivity was at 553 $m\mu$; the others showed the greatest sensitivity at 522 $m\mu$. The average threshold values of the first group of observers are smaller than those of the second group at all wave-lengths except 522 $m\mu$.

In the investigations discussed in this section, visibility curves at low intensities have been determined in three ways: (1) by the threshold method; (2) by the visual acuity method; and (3) by the equality of brightness method. For a comparison of the more important of these results Table I and Fig. 1 have been prepared. We have included for this comparison only the results obtained by the equality of brightness method. This has been done for the following reasons: (a) It has been shown by Ferree and Rand (18) and by Luckiesh (19) that spectrum lights of equal brightness do not give the same acuity; the last two methods cannot, therefore, be expected to give results which agree. (b) To what extent the threshold and equality of brightness methods give concordant results is not known. And (c) the various determinations of threshold visibility have already been compared in the recent monograph by Monroe. For comparison with the

results of these investigations, the visibility data determined in our own experiments for 0.001 m.c., dark adaptation, photometric field of 4 deg., 49 min., are included.

B. The Effect of Change of Intensity of Light on the Visibility Curve—the Purkinje Phenomenon

The fact that the relative brightness of colored lights is dependent on their absolute intensity was first pointed out by Purkinje (20) in 1825. The phenomenon as described by him included changes in the saturation and hue of the colors as well as changes of relative brightness with change of intensity. Among those who have later observed and studied the phenomenon, in most cases the brightness aspect only, may be mentioned Seebeck (21) (1837), Dove (22) (1852), Grailich (23) (1854), Aubert (24) (1865), Brodhun (25) (1887), Abney and Festing (26) (1891), and Dow (27, 28) (1906, 1910). The investigations made previous to that of Brodhun need not be considered here, however, since they merely confirm Purkinje's observations and do not give any quantitative data as to the magnitude of the phenomenon at different levels of intensity or for different wave-lengths. Brodhun claimed to find an upper limit for the Purkinje effect, at an intensity to which he assigned the value of 15 units. The unit of intensity selected by him was later used by Koenig, who defined it as follows: "diejenige Helligkeit, in welcher einem durch ein Diaphragma von 1 qmm. blickenden Auge eine mit Magnesiumoxyd überzogene Flache erscheint die in einem Abstand von 1 m. durch eine ihr parallel stehende 0.1 qcm. grosse Fläche von schmelzenden Platin senkrecht bestrahlt wird." Since 0.1 sq. cm. of platinum at the melting point has been shown to have an emissive power approximately equivalent to two English candles,[1] this unit, considered as brightness, may be represented by the brightness of a magnesium oxide surface illuminated by 2 m.c. of light, viewed through an artificial pupil of an area

[1] The Violle-Siemens photometric standard is defined as the quantity of light emitted normally by 0.1 sq. cm. of platinum at the melting point. This unit has been demonstrated to be the approximate equivalent of 2 English candles.

of 1 sq. mm. The reduction due to the artificial pupil was assumed by Hecht, (29) in recalculating some of Koenig's data, to have a value of one-fiftieth; *i.e.,* he considered 50 sq. mm. to be the area of the normal pupil under the illumination in question.

Koenig, it may be noted, disagreed with Brodhun in his conclusion that the Purkinje phenomenon ceases at 15 units of intensity. The effect of the phenomenon, according to Koenig, is very slight between 15 and 400 units, and can only be shown by large changes of intensity. Consequently it should be expected, he says, that Brodhun, who did not use intensities above 30 units, would have been unable to detect any evidence of the phenomenon above 15 units. Koenig's results will be discussed later.

Experimental evidence that there is an upper limit of intensity at which the Purkinje phenomenon ceases to be noticeable was also offered by Abney and Festing and by Dow. The experimental procedure of Abney and Festing (26) was as follows: A number of regions of the spectrum were photometered against the light from an amyl acetate lamp at different levels of intensity. Curves were plotted for each wave-length with ordinates proportional to the intensity of the colored light and abscissae proportional to the intensity of the white light. The plot for 561.3 mμ is found to be a straight line throughout the entire range of intensities investigated. The plots for wave-lengths shorter and longer than 561.3 are straight lines above a certain point; below this point they are concave and convex respectively toward the axis of abscissae. This point corresponds to an intensity equal to 1/60th of that of an amyl acetate lamp at a distance of one foot. Thus, according to Abney and Festing, the Purkinje phenomenon ceases at an intensity equivalent to approximately 1/60th f.c. or 0.167 m.c. No data as to size of field or state of adaptation are given. The range of intensities, moreover, at which determinations were made, is not stated. It is possible therefore that the criticism of Brodhun's conclusion made by Koenig applies here also.

Dow (27, 28) compared a red with a green light at a number of intensities. The photometric comparisons were made with a

Lummer-Brodhun photometer. No details as to the size of field or state of adaptation are given. The ratio of the intensities of the red and green lights was found to be practically constant above 0.2 m.c. In considering this conclusion in relation to the effect of intensity on the visibility curve it must be remembered that Dow worked at only two points in the spectrum. Consequently his results are not inconsistent with a change of shape of the visibility curve at high intensities. His results indicate merely that two particular ordinates of the curve, in the red and green respectively, keep the same ratio to one another for intensities above 0.2 m.c.

The most systematic and comprehensive data on the Purkinje phenomenon can perhaps be obtained from investigations in which the visibility curve has been determined at a number of levels of intensity. The first to furnish data of this type was Koenig. (**10**) Koenig, however, did not express his results in the form of visibility curves. This was done by Nutting in 1908 and 1910, (**30**, **12**) using the data given by Koenig.

In Koenig's investigations spectrum light of wave-length 535 mμ was used as the standard light. Photometric comparisons with this standard were made at thirteen other points in the spectrum. The standard field was kept at a constant brightness and the amounts of reduction were determined which were necessary to make the light from each of the other regions of the spectrum match the standard. No data as to size of field are given. The observations were made in a darkened room, special precautions having been taken to insure darkness adaptation in the case of the work at the lower intensities. Determinations were made by Koenig for his own eye at nine levels of intensity ranging from low to medium values. The intensities used, expressed in terms of the unit already defined (p. 18), were 590.4, 174.6, 36.9, 9.22, 2.30, 0.575, 0.036, 0.00225, and 0.00024. The lowest value was equivalent to the threshold for Koenig's eye. This specification of the levels of intensity can, however, be considered only an approximation. Three reasons may be assigned for this. (1) The standard light (535 mμ) was evaluated in terms of the above

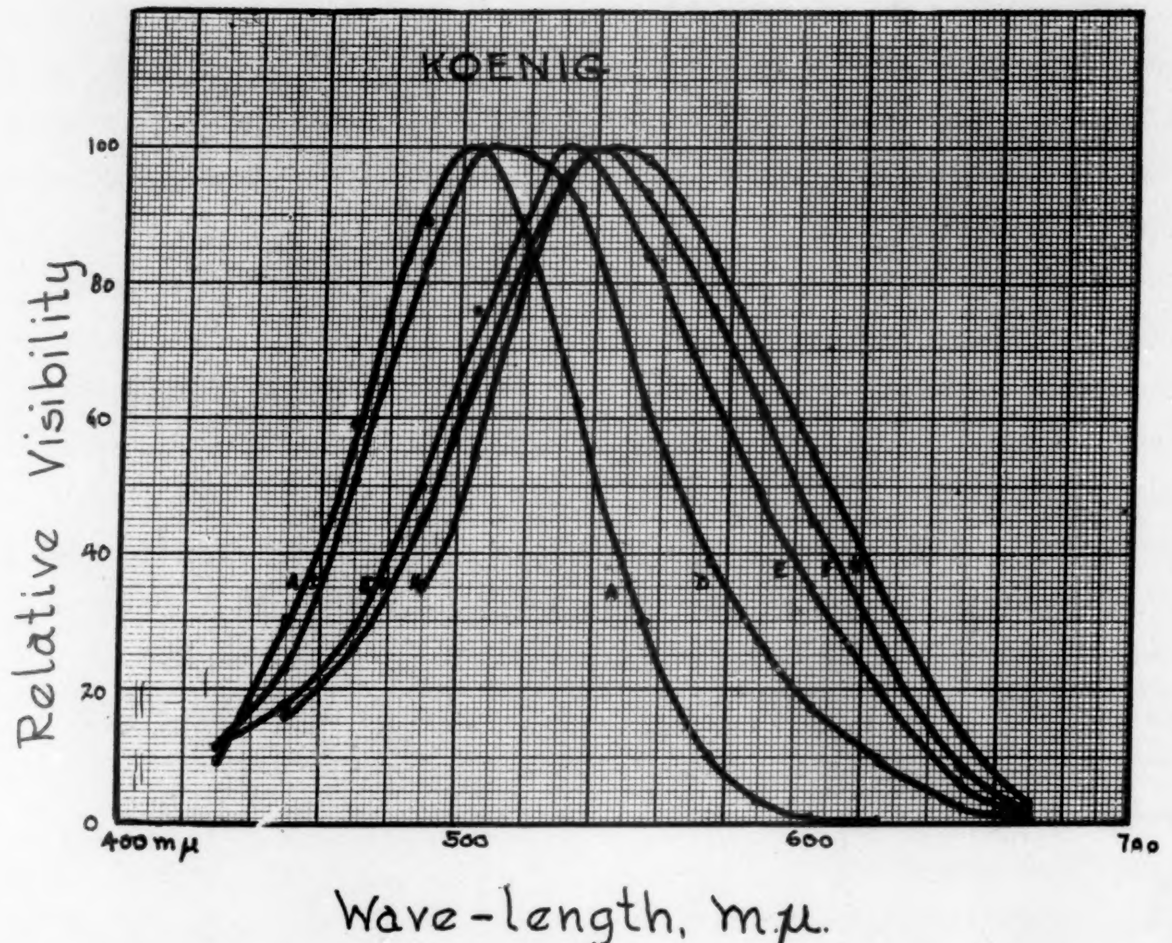


FIG. 2. Showing the visibility curves of spectrum lights under dark adaptation at nine intensities of light, as determined by Koenig; size of field not specified. The data from which these curves are plotted was recalculated by Nutting.

unit at only one level of intensity. As Koenig himself points out, this comparison should have been made at all the intensities used because of the difference in composition of the lights compared. (2) In determining the photometric value of the standard the observer was required to look first into the ocular of the spectroscope, then at the field of a Weber photometer, and so make the comparison by successive judgments rather than by a simultaneous comparison. This procedure in view of the difficult judgments involved in heterochromatic photometry, must have introduced a very considerable error. (3) The effective intensity of the light from the spectroscope was reduced to an unknown amount by the ocular slit. This slit was 1.85 mm. in height and 0.8 mm. broad; it was therefore equivalent to an artificial pupil of 1.48 sq. mm. No statement is made, however, as to whether or not such an artificial pupil was also used in the Weber photometer, the secondary standard by means of which the intensity of the green spectrum light (535 $m\mu$) was evaluated. Furthermore the primary unit of intensity in terms of which the standard is expressed involves in its definition (see p. 18) the use of an artificial pupil of a still different area, namely, 1 sq. mm. Consequently it is very difficult to judge from Koenig's article just what conditions of pupil size actually apply to the specifications of intensity given.

From the data given by Koenig on the amount of reduction that was needed in different parts of the spectrum to match the standard, and from more recent measurements of the energy distribution of a gas flame, corrected for prismatic dispersion, Nutting has calculated the visibility data for each of the nine intensities used by Koenig. The curves for the threshold and for the next three higher intensities are found to be nearly coincident. With increasing intensity the curves become broader and the point of maximum visibility shifts toward the long wave-length end of the spectrum. Nutting's data are given in Table II. The curves for certain representative intensities are shown in Fig. 2. Although the correctness of the individual curves may be questioned owing to uncertainties in the energy values and in the

correction for prismatic dispersion, the results do show that, for this particular observer at least, the selectiveness of the eye's response to intensity does not cease at the higher intensities investigated.

Ives,(31) like Koenig, made photometric measurements throughout the spectrum but did not present his results as visi-

TABLE II

Showing the relative visibilities of spectrum lights under dark adaptation at nine intensities of light, as determined by Koenig; size of field not specified. The data given in this table were recalculated by Nutting. For a definition of the unit in terms of which the intensities were specified, see p. 18.

Wave-length	T	A	B	C	D	E	F	G	H	
	0.00024	0.00225	0.036	0.575	2.30	9.22	36.9	147.6	590.4	Illumination Units
430 mμ	8.1	9.3	12.7	12.8	11.4	11.4				
450	33.0	30.0	29.0	31.0	23.0	17.5	16.0			
470	63.0	59.0	54.0	58.0	51.0	29.0	26.0	23.0		
490	96.0	89.0	76.0	89.0	83.0	50.0	45.0	38.0	35.0	
505	100.0	100.0	100.0	100.0	99.0	76.0	66.0	61.0	54.0	
520	88.0	86.0	86.0	94.0	99.0	85.0	85.0	85.0	82.0	
535	61.0	62.0	63.0	72.0	91.0	98.0	98.0	99.0	98.0	
555	26.0	30.0	34.0	41.0	62.0	84.0	93.0	97.0	98.0	
575	7.4	10.2	12.2	16.8	39.0	63.0	76.0	82.0	84.0	
590	2.5	3.4	5.4	9.1	27.0	49.0	61.0	68.0	69.0	
605	0.8	1.2	2.4	5.6	17.3	35.0	45.0	54.0	55.0	
625	0.4	0.4	1.1	2.7	9.8	20.0	27.0	35.0	35.0	
650	0.0	0.0	0.3	0.7	2.5	6.0	8.5	12.2	13.3	
670	0.0	0.0	0.1	0.2	0.7	1.7	2.5	3.0	3.0	

bility data. The measurements were made for three sizes of field and at a number of levels of intensity. The work was done for the purpose of making a comparison of the flicker and equality of brightness methods of photometry. The data for the equality of brightness method only will be considered here. The standard field consisted of a magnesium oxide surface illuminated by a carbon lamp operated at 4 watts per candle. For each curve this field was kept at a constant level of brightness and the spectrum light was made to match it in intensity. In most cases determinations were made at 13 points in the spectrum. As already indicated, the data given by Ives have not been corrected for the energy distribution in the spectrum of the source of light employed; therefore the curves plotted by him cannot be compared with visibility curves. It might be expected, however, that the changes which take place in the curves with changes in size of

field and in intensity are of the same type as would have been obtained if the results had been reduced to visibility data by applying the correction for energy distribution.

Three sizes of field were used in the investigation; two circular fields whose diameters subtended visual angles of 1.86 deg. and 4.58 deg., respectively, and a rectangular field whose dimensions are given as 5.15 by 8.6 deg.[1] Data are presented for the following levels of intensity: 1.25, 2.85, 8.9, 68 and 270 m.c. "These illuminations," Ives states, "because of the artificial pupillary aperture of 1 sq. mm., correspond to lower illuminations in practical photometry; they will therefore be referred to here as 'illumination units'." In a later article (32) Ives determined for a number of observers the amount of illumination which, received through an artificial pupil with an area of 1 sq. mm., is equivalent to 25 m.c. for the normal pupil. The amount of illumination required by the different observers was found to differ by as much as 100 per cent. Ives found for his own eye that the effective intensity was reduced to 1/12 the original value by the use of an artificial pupil of these dimensions. The observer's eyes were probably in a state of partial light adaptation as is indicated by the following quotation: "In ordinary photometry the eye is probably in the condition called by physiologists 'light adapted' because of the order of illumination used, and because of the use of auxiliary lights for such things as scales and data sheets. . . . The policy in the present investigation has been to maintain the conditions of lighting at nearly those of practical photometry. . . ."

Ives summarizes his results as follows: "The effect of decreasing illumination is twofold: first occurs a broadening of the curves (increase of area), then an increase on the blue side, which results in a shift of the whole curve toward the blue. This may be interpreted as an increase on the red side, followed by an increase on the blue side, the latter becoming more marked at

[1] The latter field is described as an oblong 18 by 24 mm., viewed at a distance of 20 cm. This is equivalent to a visual angle of 5.16 x 6.866 deg. The value 8.6 deg. is probably a misprint.

lower illuminations. With decrease in the size of the aperture these changes are much less, which is in accordance with the oft encountered statement that the Purkinje effect is absent for very small fields." The intensity level at which a *decided* shift toward the blue occurs is different for the two observers. The curves for one observer show this increase in sensitivity to blue between 68 illumination units and 8.9 illumination units for both the large and the medium sizes of field. The curves for the other observer, however, for the medium size of field, 4.58 deg., do not show a marked change in blue sensitivity until the next lower intensity, 2.85 illumination units, is reached. In the case of the smallest field size, the curves for both observers show only very slight changes as the result of change of intensity.

Ferree and Rand (33) investigated the selectiveness of the achromatic response of the eye to wave-length by three methods, which they describe as follows: " (a) a comparison at different intensities of the photometric value of stimuli made equal in energy value; (b) a similar comparison of stimuli having the relative energy values of a prismatic spectrum of given type; and (c) a comparison at different intensities of the energy values of stimuli made equal photometrically." The amounts of energy were measured by means of a bismuth-silver thermopile and a galvanometer of the Thompson type constructed by Coblentz.

Methods (a) and (b) were used in the investigation of a range of low intensities. In the first method, luminosity data were obtained for four equal energy spectra whose values sustained to each other the following ratios: 1, 1/2, 1/4, and 1/12. In the second method, luminosity determinations were made of the prismatic spectrum of a Nernst filament, and of this same spectrum when the energies were reduced in the following ratios: 1/2, 1/12 and 1/45. Some of the data obtained by method (a) are given in Table III. In this table a low percentage indicates a relatively rapid change in photometric value for a given change of physical intensity; and conversely a high percentage indicates a relatively slow change in photometric value. The slowest rate of darkening is seen to be in the region from 522 to 463 mμ.

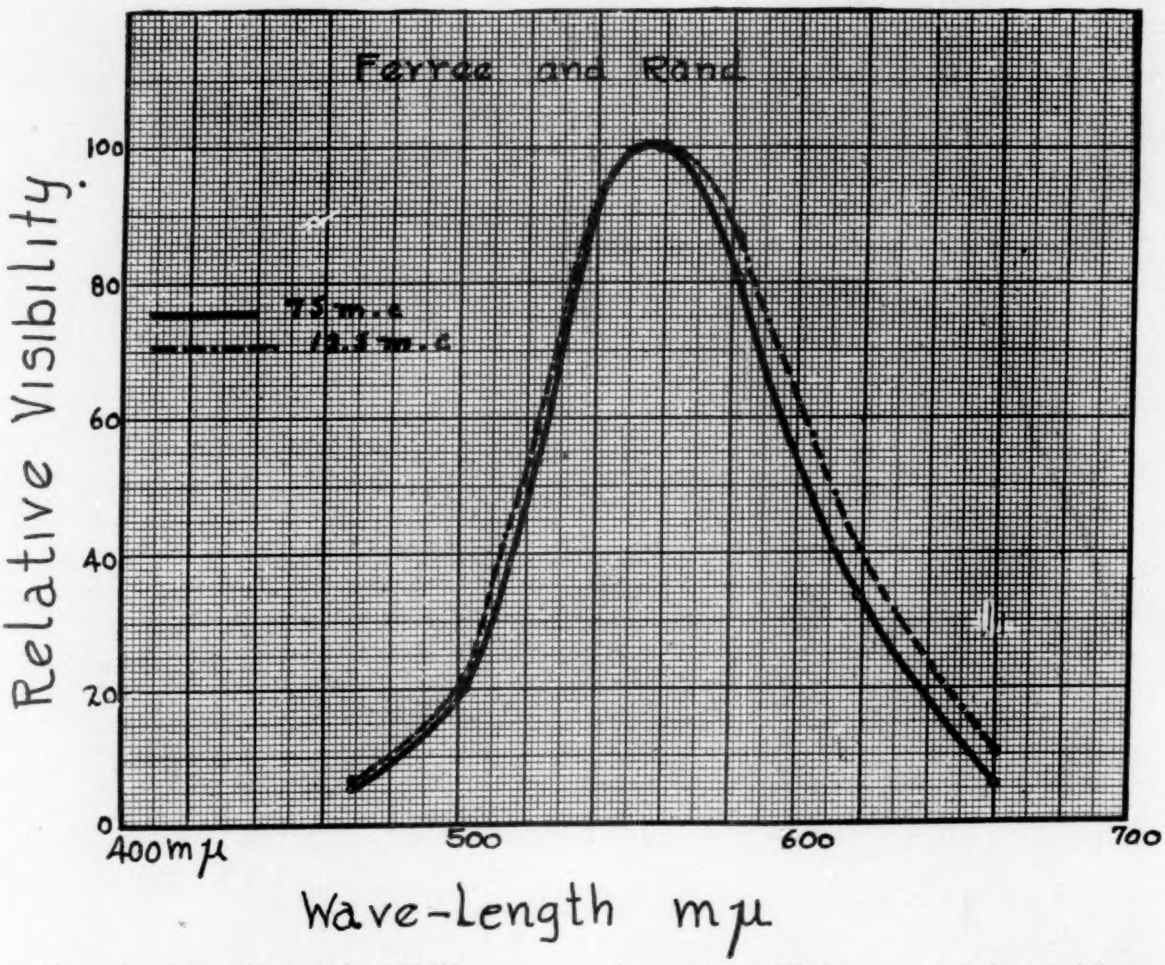


FIG. 3. Showing the visibility curve of spectrum lights at two intensities, as determined by Ferree and Rand; light adaptation; size of field 4 deg. 18 min.

Using method (c), determinations were made at four high intensities, namely 75, 50, 25, and 12.5 m.c. Measurements were made at seven points in the spectrum of the relative amounts of energy required to match a magnesium oxide surface illuminated by these four intensities of white light. In making the photometric determinations the equality of brightness method of photometry was used. The photometric field subtended a visual angle of 4 deg. 18 min. Since the different illuminations of the magnesium oxide surface were obtained by varying the distance of a lamp from this surface, the eye was at a level of adaptation corresponding approximately to that of the intensity under investigation. This situation corresponds to that ordinarily occurring in photometry when the photometer lamps are not enclosed in a light-proof housing.

TABLE III

Showing the change in the selectiveness of the achromatic response of the eye to wave-length produced by varying the intensity of light, as determined by Ferree and Rand. In this table are shown in per cent of the original value the photometric values of each of the colored lights when their energy values have been reduced respectively to 1/2, 1/4, and 1/12 of the values present in equal energy Spectrum A. The changes in the deviations of the relative photometric from the relative radiometric values produced by the changes of intensity may be noted by comparing the percentages in Column 2 with 50 per cent; in Column 3 with 25 per cent; and in Column 4 with 8.33 per cent.

Wave-length	Relation of Photometric Value of 1/2 A to A Expressed in Per Cent	Relation of Photometric Value of 1/4 A to A Expressed in Per Cent	Relation of Photometric Value of 1/12 A to A Expressed in Per Cent
655 mμ	47.96	15.31	1.53
616	49.07	26.02	7.66
580	44.12	24.26	10.29
533	47.76	23.88	19.33
522	54.92	33.61	22.95
488	74.65	55.63	36.83
463	66.83	34.27	30.60
439	46.43	29.29	22.86

Data obtained by this method are given in Tables IV–V and Fig. 3. Table IV shows the changes in energy required at each wave-length to produce given changes in photometric value. To quote the authors' conclusions in regard to these data: "The results show first of all, it will be noted, that change in selective-

ness of response with change of intensity is still present in the region of the intensity scale included between 50 and 75 meter-candles, as well as in the regions included between 25 and 75 meter-

TABLE IV

Showing the change in the selectiveness of the achromatic response of the eye to wave-length produced by varying the intensity of light as determined by Ferree and Rand. In this table are shown in per cent of the original value, the energy value of the stimuli when their photometric values have been reduced from 75 to 50 meter-candles; from 75 to 25 meter-candles; and from 75 to 12.5 meter-candles. A high per cent energy value indicates that a relatively small decrease in energy is needed to produce the desired decrease in photometric value or that there is a relatively rapid darkening of the color with decrease of energy.

	Per Cent of Energy Value to Original Value when Photometric Value Has Been Reduced from		
Wave-length	75 to 50 Meter-Candles	75 to 25 Meter-Candles	75 to 12.5 Meter-Candles
660 mμ	50.4	17.4	7.0
619	52.9	22.1	10.3
582	53.8	24.0	11.5
560	55.0	25.0	12.5
523	55.8	25.0	11.5
502	60.0	23.3	11.7
469	53.5	24.2	9.6

candles and 12.5 and 75 meter-candles. A closer scrutiny shows further that in case of the reduction from 75 to 50 meter-candles the most rapid darkening with a decrease of energy occurs in the region of the blue-green. This effect is, it will be remembered, quite the opposite of that which was obtained at the lower intensities treated of earlier in the paper." . . . "At these intensities the slowest darkening was obtained in the region of the blue-green and the most rapid in the region of the red. Moreover, for the reduction 75 to 12.5 meter-candles, the region of most rapid darkening shifts to the middle of the spectrum. In short, in

TABLE V

Showing the relative visibilities of spectrum light at four intensities as determined by Ferree and Rand; light adaptation, size of field, 4 deg. 18 min.

Wave-length	75 m.c.	50 m.c.	25 m.c.	12.5 m.c.
660 mμ	5.87	6.40	8.41	10.54
619	33.72	35.01	38.06	40.95
582	80.435	82.14	83.23	86.96
560	100.0	100.0	100.0	100.0
523	53.68	53.87	53.53	58.08
502	19.99	18.34	21.38	21.42
469	5.18	5.32	5.36	6.73

passing from high to low intensities the region of most rapid change in selectiveness of achromatic response seems to shift from a region in the short wave-lengths at the high intensities, through the middle of the spectrum at the intermediate intensities, to the long wave-lengths at low intensities."

In Table V the results are given in the form of visibility data for all the intensities employed. In Fig. 3, however, only two of the intensities, 75 and 12.5 m.c., are represented. The curves for the two remaining intensities, 50 and 25 m.c., would if plotted occupy an intermediate position. Both the curves and the tabular data show that for the range of intensities investigated the visibility curve broadens with decrease of intensity. The change is greatest on the long wave-length side of the curve.

The most recent investigation in which visibility curves have been determined at different intensities is that of Laurens,(16) published in 1924. The relative energy distribution of the spectrum was measured by means of a bismuth-silver thermopile similar to that used by Ferree and Rand. The photometric determinations were made in some cases by the flicker method and in others by the equality of brightness method. The results given for the three higher intensities, 25, 10, and 2.5 m.c. will not be considered here since the data were obtained either by the flicker method alone or by averaging results obtained by both methods. The curves for 1 m.c. and 0.2 m.c. were determined entirely by the equality of brightness method. Laurens states that the observer was dark-adapted for the determinations at the low intensities but does not state which of the five were considered as "low intensities." Also he does not give any information as to the adaptation conditions in the case of the other intensities. At the higher of the two intensities, 1 m.c., the point of maximum visibility was found to be near 550 mμ; at 0.2 m.c. it had shifted to 510 mμ and the curve had become narrower. In comparing these results with others, however, two important experimental conditions in Laurens' investigation should be noted. (1) From the description of his apparatus it is apparent that an artificial pupil of approximately 1.25 sq. mm. was used. This conclusion

is further borne out by the fact that Laurens states that the intensity level designated as 0.2 m.c. is below the chromatic threshold. Such an artificial pupil would very greatly reduce the effective intensities since the normal size of pupil for the dark-adapted eye is quite large. (2) A very small photometric field (2 deg.) was used. The fact that no marked Purkinje shift occurred until the lowest intensity was reached, is probably due, Laurens states, to the use of this small stimulus field.

A survey of the foregoing studies brings out the following points. (1) The results of Ferree and Rand, Ives, and Koenig all show that the visibility curve continues to change with change of intensity throughout the entire range investigated. Koenig's results, however, differ somewhat from those of the other two, since he found that with increase of intensity the curves broaden and shift gradually toward the long wave-length end of the spectrum. The data of Ives and of Ferree and Rand indicate that at the higher intensities the visibility curve broadens with decreasing intensity, while the point of maximum sensitivity remains unchanged. Both of these latter investigations were made under light adaptation, it will be remembered, while Koenig's data were obtained under dark adaptation. (2) The more marked Purkinje effect occurs at the lower intensities. This effect, as determined by Ives and Laurens, consists of a shift of the whole curve toward the short wave-length end of the spectrum. When intensities near the threshold are used the point of maximum sensitivity is found to be in the region of 510 mμ as was shown in the preceding section. The maximum at high intensity is according to the results of Ferree and Rand at approximately 560 mμ. This is in agreement with the results obtained by Hyde, Forsythe, and Cady as will be shown in the next section. (3) The intensity at which the marked Purkinje shift occurs was found by Abney and Festing to be approximately 0.167 m.c. and by Dow 0.2 m.c. Definite values for this illumination can not be obtained from the data of Laurens and Ives because their use of an artificial pupil makes it impossible to determine the effective intensities employed by them.

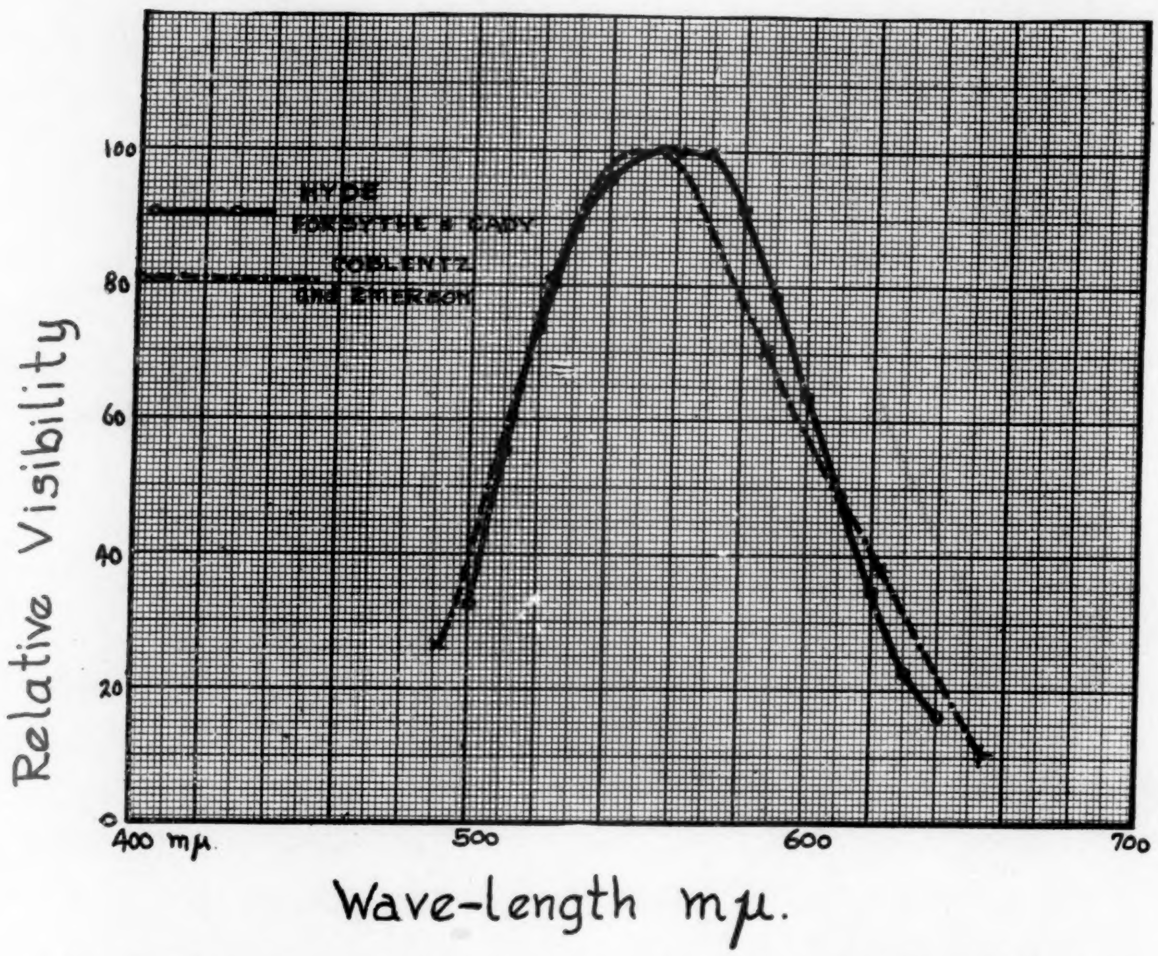


FIG. 4. Showing the visibility curves for high intensities of spectrum lights, as determined by Coblentz and Emerson and by Hyde, Forsythe and Cady.

C. The Visibility Curve at High Intensities

In addition to the investigations of the visibility function made at a number of levels of intensity, several others dealing with visibility at a single high intensity should be mentioned. Coblentz and Emerson, Hyde, Forsythe and Cady, and Gibson and Tyndall have all published data on average visibility at high intensity for a large number of observers.

Coblentz and Emerson's determinations (34) are for an intensity of 50 m.c. reduced to an unknown value by the use of an artificial pupil, 2.36 x 0.52 mm. The photometric field was surrounded by a " white field." The apparatus was used in a dark room. Cloth screens prevented stray light from the apparatus from reaching the eye of the observer. The visibility determinations were made by 110 observers. Most of the data were obtained by the flicker method of photometry. Determinations by the equality of brightness method were made only at the following wave-lengths, 493, 523, 587.6, 623 and 654 $m\mu$. Unfortunately, none were made at or near the point of maximum visibility. If the data given by Coblentz and Emerson are plotted and a smooth curve drawn through the points at which determinations were made, the region of maximum sensitivity is found to be near 550 $m\mu$. In order to compare their results with those of other investigators the values given by Coblentz and Emerson have been reduced in the proportion necessary to give the maximum ordinate of the visibility curve a value of 100. This curve is shown in Figure 4. The data from which it was plotted are given in Table VI.

Hyde, Forsythe and Cady, (35) in 1915, determined an average visibility curve for a number of observers. Their object was to obtain visibility data by the equality of brightness method which, in conjunction with Planck's equation could be used to calculate the relative luminosity curve of the spectrum of a black body.

The procedure was as follows. The luminosity curve of each observer was first obtained by a modification of the cascade method of photometry. The spectroscope used was furnished

with a special collimator slit the upper half of which was displaced 0.15 mm. in a lateral direction relative to the lower half. The slit was 0.1 mm. in width. For a given setting of the instrument, the upper and lower halves of the photometric field were illumi-

TABLE VI

Showing the relative visibilities of spectrum lights at an intensity of 50 m.c., reduced by an artificial pupil 2.36 x 0.52 mm., as determined by Coblentz and Emerson; data averaged from results of 110 observers; photometric field surrounded by a white field; size of field 2 deg. Data given in column 2 are from tables by Coblentz and Emerson; in column 3 the original data have been reduced to a scale in which 100 represents the value of the maximum ordinate of the smoothed curve drawn through the points plotted from the data determined experimentally.

	Visibility	
Wave-length	Data Given by Coblentz and Emerson	Data Reduced to Give Maximum of Curve a Value of 100
493 mμ	30.08	26.1
523	92.98	80.5
587.6	81.51	70.6
623	44.2	38.3
654	12.13	10.5

nated by light of slightly different wave-lengths, which may be designated as λ and $\lambda + \Delta_\lambda$. Each observer determined at 18 points the relative luminosities of the upper and lower halves of the field. The values of the ratio $R = \dfrac{L_\lambda}{L_\lambda + \Delta_\lambda}$ where L_λ indicates the luminosity of the field illuminated by light of wave-length λ, were plotted against wave-length and a smooth curve drawn through the 18 points. By interpolation, the value of this ratio could be determined at any other point that was desired. From this curve the luminosity curve for the individual in question was obtained by successive multiplications. The average luminosity curve for all the observers was next determined from the individual curves. From these data and from the energy distribution of the spectrum, the visibility at each wave-length was obtained by dividing the luminosity value at that wave-length by the corresponding energy value.

Results obtained by this method obviously are not equivalent to visibility data determined for a constant level of brightness, unless

we assume that, for the range of intensities used, the ratio of the lumen to the watt for a given point in the spectrum is a constant. The luminosity of the spectrum used varied from 30 to 150 m.c. The effective values of luminosity were, however, much less than this owing to the use of an artificial pupil of only

TABLE VII

Showing the relative visibilities of spectrum lights at an intensity of 754 m.c. as determined by Hyde, Forsythe and Cady; data averaged from results of 10 observers; size of field and state of adaptation not specified.

Wave-length	Visibility	Wave-length	Visibility	Wave-length	Visibility
500 mμ	32.9	550 mμ	99.3	600 mμ	63.9
510	55.2	560	100.0	610	48.9
520	73.6	570	99.9	620	34.7
530	88.6	580	91.4	630	22.9
540	95.8	590	78.2	640	16.1

0.6 sq. mm. in area. It scarcely seems allowable then to assume that the Purkinje effect was entirely negligible for this range of intensities.

The same authors have also determined a visibility curve at a constant brightness level of 0.024 candles per sq.cm. (approximately 754 m.c.) This investigation was made by means of a spectral pyrometer. The filament of an incandescent lamp, placed in the focal plane of the spectroscope, served as a constant comparison field. A green glass screen, whose transmission values throughout the spectrum were known, was used to reduce the color difference between the two fields compared. The size of field and state of adaptation are not specified. The average curve of the 10 observers used is shown in Fig. 4. Data for this curve are given in Table VII. The maximum visibility occurred at 560 mμ. Curves and tables for the visibility determinations at unequal brightness levels will not be included here.

Gibson and Tyndall (36) in 1923 also determined the average visibility curve for a large number of observers, using the cascade method. Like Hyde, Forsythe and Cady they measured visibility in lumens per watt and made their determinations not at a constant brightness level, but with the distribution of intensities as it occurs in the spectrum. At 580 mμ, the region of maximum

luminosity, the intensity was approximately 530 m.c. The photometric field was 3 deg. in diameter. The state of adaptation is not specified, but owing to stray light from the apparatus, it is probable that the observers were partially light adapted.

D. The Effect of State of Adaptation of the Eye on the Visibility Curve

The effect of state of adaptation on the relative sensitivity of the eye in its achromatic response to wave-length of light has received little attention in the work of previous investigators. That the eye changes its absolute sensitivity with change of state of adaptation is generally known; but that its selectiveness of response to wave-length also changes with its preadaptation or presensitization to light has received but little recognition either in theory or in laboratory practice.

A dependence of the difference in amount of light required to arouse the threshold sensation in a light and dark room upon the color of the light used as stimulus was observed by Dove (22) as early as 1852. He apparently had not considered, however, that this phenomenon sustains any relation to the state of adaptation of the retina. He had regarded it merely as a local reaction in the retina contingent upon the lower level of intensity at which the threshold is obtained. That is, less light is required in a dark than in a light room to arouse the threshold sensation. In accord with the Purkinje phenomenon, this in itself, he thought, should result in a relative increase in the brightness of a blue stimulus as compared with the red, or a change in the relative sensitivity to these two colors.

This explanation of the eye's difference in relative sensitivity in the light and in the dark seems not to have met with criticism until 1895. At this time Hering (37) published results which he claimed could not be ascribed alone to a local reaction in the retina due to a decrease in the intensity of the stimulus light. These results were obtained in three sets of experiments. In the first he used red and blue pigment stimuli, the illumination of

which was made independent of that of the room. When these stimuli were made equally bright and the light falling upon them was decreased without changing the general illumination of the room, there was no evidence of a relative increase of the brightness of the blue. He describes, in fact, what might be called a reverse Purkinje effect. "Oft genug erscheint das blaue Feld schon schwarz während das rothe noch etwas Farbe zeigt und deshalb etwas heller (minder dunkel) erscheint als das blaue." In a second set of experiments lights transmitted through red, green, and blue glass were used as stimuli; and in a third, two fields illuminated by spectrum lights. These fields were in both cases surrounded by a neutral background illuminated by colorless light. In neither case was there any evidence of a Purkinje effect following a decrease of intensity of the stimulus light, provided that the light in the room and therefore the state of general adaptation remained unchanged. If, however, the illumination of the room was decreased simultaneously with the decrease in the intensity of the stimulus both colors appeared to gain in brightness but the blue more than the red. This effect he found to become more pronounced with increase in length of exposure to the darkened room. From the results of these experiments Hering concludes that the customary Purkinje shift in the relative brightness of the colors is not due alone to a local reaction in the retina; it occurs only in connection with a change in the state of general adaptation of the eye. What he calls "Momentan-Adaptation" is sufficient to cause the phenomenon but the effect is increased as the state of adaptation becomes more complete.

In the same year, Parinaud (**38**) also made a study of the effect of adaptation on relative sensitivity. The effect on the threshold of the achromatic sensation was determined at several points in the spectrum. He found that for the wave-lengths in the red the same results were obtained under light and dark adaptation. At other points in the spectrum an increase in sensitivity was found for dark adaptation which was greatest for the short wave-lengths. No mention is made of the length of adaptation period employed. The effect of dark adaptation on the color sensations

is, Parinaud points out, similar to that produced by adding white light to the stimulus, *i.e.*, the color becomes brighter but less saturated as the eye becomes dark-adapted. Since the energy distribution in the spectrum used was not determined, the results given by Parinaud have no quantitative significance.

The effect of state of adaptation on the achromatic response has a very important bearing on photometry and on all uses of the eye in which a comparison of lights has to be made in terms of luminosity or subjective brightness. Although it might be inferred from the observations of Hering and perhaps from certain published photometric data that photometric matches are affected by the state of adaptation of the eye, there has been no systematic investigation of the effect nor any recognition of state of adaptation as one of the variable factors which may affect the results obtained in the practice of heterochromatic photometry.

E. The Effect of Size Field on The Visibility Curve

A number of investigators have claimed that the Purkinje phenomenon does not occur when a sufficiently small stimulus is used. Others claim, on the contrary, that under such conditions the Purkinje phenomenon is still present although diminished in amount. The sizes of field used by these investigators, when specified, range from point area to fields subtending visual angles of approximately 2 deg. In some cases the writers merely state that a foveal stimulus was used. We shall consider first those investigations in which the phenomenon is found to be absent in the fovea.

Parinaud, (38) whose investigation was discussed in the last section, found, it will be remembered, that an irregular increase in threshold sensitivity to wave-length occurred with dark adaptation. When stimuli of point area were used this change in sensitivity did not occur. From this he inferred that the relative threshold sensitivity to wave-length at the fovea is not affected by a change from light to dark adaptation.

The next evidence obtained to show that this phenomenon is

lacking in the fovea was presented by von Kries (39) in 1896. His data were obtained from three sets of experiments. In the first, he used red and blue pigment stimuli which under daylight illumination, intensity not specified, appeared to the eye as equally bright. At the midpoint of the line separating the two fields, a small hole, covered with milk glass illuminated from behind, served as a fixation object. The pigment stimuli subtended a visual angle of approximately 1 deg. When they were viewed in a dim light with a dark-adapted eye and uncontrolled fixation the blue was seen brighter than the red, *i.e.*, the Purkinje phenomenon was present. When, however, the luminous point was fixated the blue became less bright and was seen approximately equal in brightness to the red. In the second set of experiments a Helmholtz color-mixer was used. By means of this apparatus light at 480 mμ was compared in turn with lights at 670.8 and 589 mμ. When a foveal size of field was used, von Kries found no evidence of a Purkinje phenomenon within the limits of accuracy of heterochromatic photometry, even though the lights were reduced to approximately threshold intensities.

The third set of experiments was conducted in collaboration with Nagel in 1900. (40) In these experiments a photometric field was used consisting of a circular area surrounded by a concentric ring of red paper. The red paper was illuminated by light from a Welsbach mantle filtered through red glass. A small knot tied in black thread was used as a fixation point. The two fields were brought to brightness equality as judged by a light-adapted eye. They were then viewed with a dark-adapted eye with and without control of fixation. In the former case the Purkinje effect was absent; in the latter it was present. The experiments were repeated with light transmitted through a yellow-green filter as a substitute for the spectrum light. Similar results were obtained.

These investigators also made quantitative determinations of the extent of the area in which the Purkinje phenomenon is found to be absent. They used a disc of red paper containing a circular aperture 15 min. in diameter, arranged so that it could

be moved either horizontally or vertically. The yellow-green field was observed through this aperture with a dark-adapted eye. The observer maintained his fixation while the hole was displaced as far as could be from the point of regard without disturbing its match with the surrounding field. The extent of this zone for one eye was found to be 107 min. in the horizontal direction and 81 min. in the vertical. No indication is given with regard to how much should be added to the breadth of this zone as an allowance for the effective width of the concentric red ring which formed a part of the photometric field.

Experimental evidence has also been presented by Troland (41) that the Purkinje phenomenon does not occur in the fovea. He used a circular field of 1 degree in diameter, viewed against a dark background. A central red band, 0.34 deg. in width, was illuminated with light of wave-lengths ranging from 654 to 687 $m\mu$. The rest of the field was filled with blue light, 469–481 $m\mu$. A luminous fixation point, just visible to the dark-adapted eye was employed. The field was viewed through an artificial pupil with a diameter of 1.36 mm. The subject, after 5 minutes of light adaptation, adjusted the red and blue fields either to equality or so that the red field was slightly brighter than the blue. The intensity of the light in the blue field was 50 photons. The method used in making the observation is described by Troland as follows. " The subject was now given 30 minutes complete dark adaptation, after which he was required to fixate carefully the luminous point. Immediately upon establishment of fixation, the original field was suddenly exposed to view, with the first selected relative intensities accurately maintained, but with a reduction of the absolute intensity of both components to 1/32 of the value at which the bright adaptation setting was made." The experiments were then repeated with an intensity of 31 photons in the blue field and 20 min. of light adaptation. Troland himself acting as observer found not the slightest trace of a Purkinje effect in either case. Observations by two inexperienced subjects under the same conditions, however, yielded conflicting

results which should be attributed, Troland believes, to their inability to fixate accurately.

Several investigators, namely, Koster, Sherman, Hering, Dow, Ives, and Gallissot, have claimed to find a slight Purkinje effect in the fovea. The first of these, Koster,(42) in 1895, states that between the central and peripheral parts of the retina there is a quantitative but not a qualitative difference in respect to light and color sensitivity. His observations were made with a stimulus field 5 mm. square which, viewed at a distance of 500 mm. subtended a visual angle of 35 min. The apparatus was so arranged that the stimulus presented two equal contiguous surfaces, one reflecting red and the other blue spectrum light. No special provisions were made for control of fixation. That he did not adequately control fixation might account for the slight Purkinje effect he obtained.

Sherman's experiments were published in 1898.(43) He used a field subtending an angle of 2 deg. 11 min., composed of red and violet stimuli which were made equal in brightness at a high intensity. These stimuli were obtained from colored gelatine filters transmitting light from 714 to 676 mμ and from 461 to 422 mμ, respectively, illuminated from behind by a Welsbach lamp. Reductions in intensity were produced by changing the distance of the lamp and by interposing in the beam of light filters of smoked glass which were approximately neutral as to color. An eccentric fixation point was used which made an angle of 10 deg. with the line of regard. It was claimed by Sherman that if the eye moved the movement of this point in the peripheral field was very noticeable. It is conceivable, however, that a very gradual movement of the eye would escape detection. Sherman found a range of low intensities for which the violet portion of the field was brighter than the red. He points out the importance of being able to change the intensity continuously in order to detect the Purkinje phenomenon. Other investigators would be inclined to attribute Sherman's success in demonstrating the brightness shift to the size of field employed, rather than to the method of changing the illumination of the field. These investi-

gators claim that a size of field smaller than 2 deg. must be used to demonstrate the absence of the Purkinje phenomenon.

Hering, (44) working in 1915, found a momentary Purkinje effect at the first instant of fixation, when a field subtending a visual angle of 2.08 degrees was employed. This was demonstrated as follows. Red and blue spectrum lights were used as stimuli. The intensities of these lights were so adjusted that, with light adaptation and accurate fixation of the center of the field, the brightness of the blue was either equal to or less than that of the red. The intensities of both sources were then reduced in the same proportion. Before the observations were begun, the observer's eyes were dark adapted and the blue light was excluded from the field. The center of the field was then fixated and the blue light turned on. For an instant it appeared brighter than the red. For observers unpracticed in taking an accurate and precise fixation at will, a different procedure was used. For these observers the blue light was not excluded from the field. The observer was directed first to take an eccentric fixation, then to shift the eyes quickly to the central fixation point. Again for an instant the blue field appeared brighter than the red. In the first procedure, as Troland has pointed out, the observer could become fatigued to the red stimulus before the blue was turned on. By means of the second procedure, this difficulty is avoided, but it is almost impossible to be sure that the proper fixation was obtained at the critical instant. Troland claims also that the field size used was too great.

Dow, (27, 28) in 1906 and 1910, investigated the effect of both field size and intensity on photometric determinations. A red light was photometered against a green light. The changes in field size were brought about by varying the distance of the observer's eye from the photometric field. Dow finds that the red becomes " more and more accentuated as the eye recedes," this effect being greatest at the lowest illuminations. In other words, when a red and a green light are compared, decrease in the size of the photometric field is accompanied by a reverse Purkinje phenomenon.

Photometric measurements made by Ives (31) in 1912 for three sizes of field also bear on this question. He found that change of size of field has very little effect at high intensities. As the intensity is decreased, however, the effect of size of field increases. The general tendency seems to be an increase of red sensitivity and a decrease of blue sensitivity with decrease in size of field. These results, as we have already pointed out, were obtained under conditions of partial light adaptation.

In 1910 Gallissot (45) investigated the photometry of point sources of light at different intensities, in order to determine the effect of the Purkinje phenomenon on estimates of the magnitude of stars. He concludes that "Le sens du phénomène pour les points lumineux est l'inverse de celui constaté pour les plages, c'est-à-dire que, si l'on diminue dans le même rapport les éclats de deux points lumineux rouge et bleu estimés de même éclat, le rouge paraît plus brillant." . . . "Les mesures effectuées sur les éclats faibles sembleraient indiquer que le phénomène se passe alors pour les points comme pour les plages. A la limite de la visibilité, les teintes ne se différencient pas; on est tenté d'observer par vision oblique, et dans ce cas, le point bleu jugé primitivement d'éclat plus faible que le point rouge, paraît nettement plus brillant."

All the cases in which a Purkinje effect has been found in the fovea might, as we have seen, be explained as due, either to the use of too large a field size, or to lack of proper control of fixation. On the other hand, it is possible that, if a *continuous* variation of intensity were made, as in Sherman's procedure, a Purkinje effect might have been found by those experimenters who deny its existence in the fovea. Moreover, none of the investigators, excepting Parinaud and Ives, made determinations at more than two or three points in the spectrum. Ives, it will be remembered, found a reverse Purkinje effect with light adaptation. Parinaud's observations dealt only with the question of effect of adaptation at the threshold. Before the question can be settled, therefore, visibility curves must be determined, for both

light and dark adaptation, with small field sizes and accurate fixation control, at a sufficient number of points in the spectrum and for a sufficient range and number of levels of intensity. This is one of the points investigated in the experimental section of the present study.

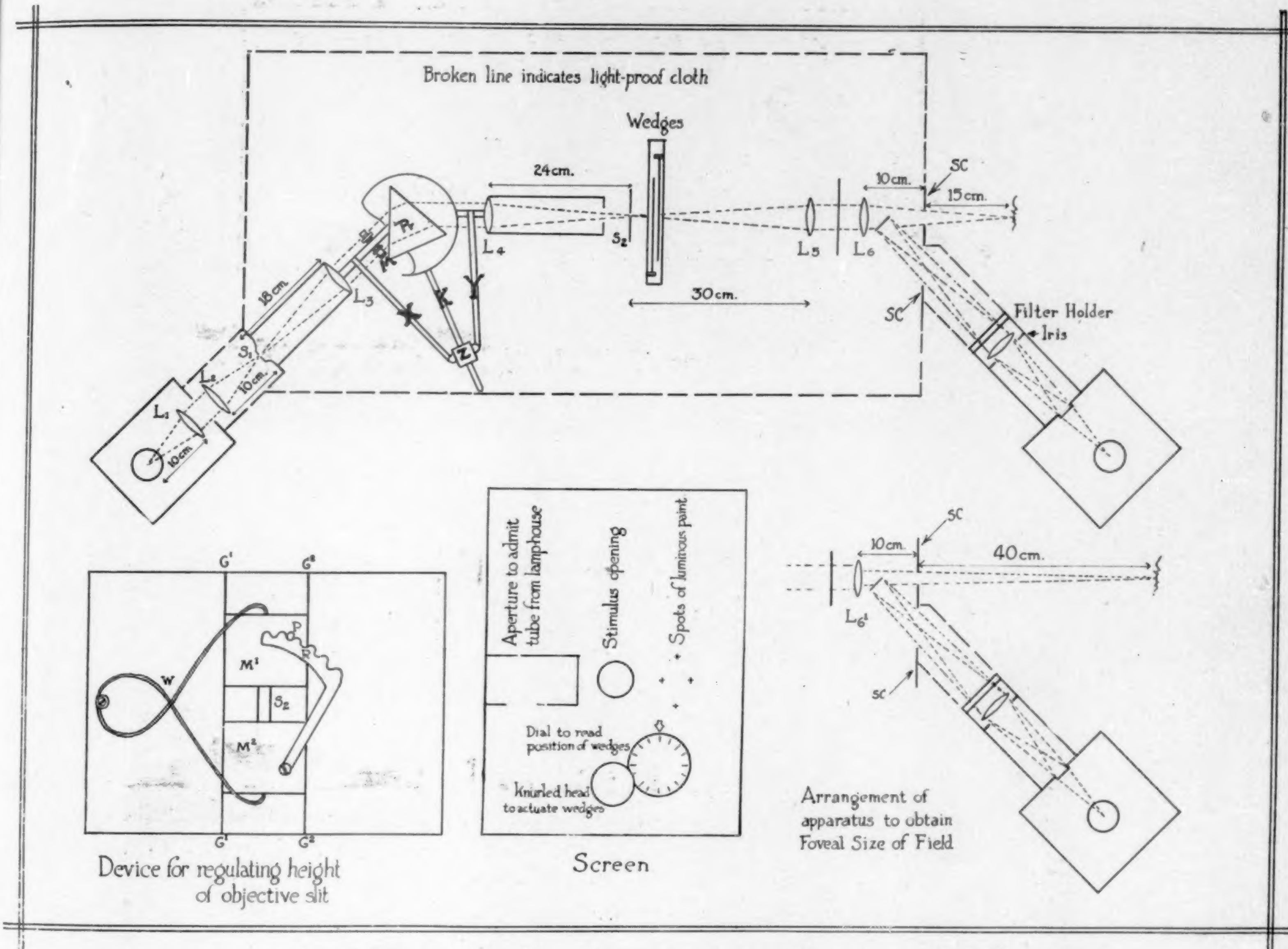


FIG. 5. Drawing of apparatus showing the path of beam of light from the source to the eye, the arrangement of apparatus to obtain foveal size of field, the device for regulating height of objective slit, and the front screen of the light-proof compartment enclosing the apparatus.

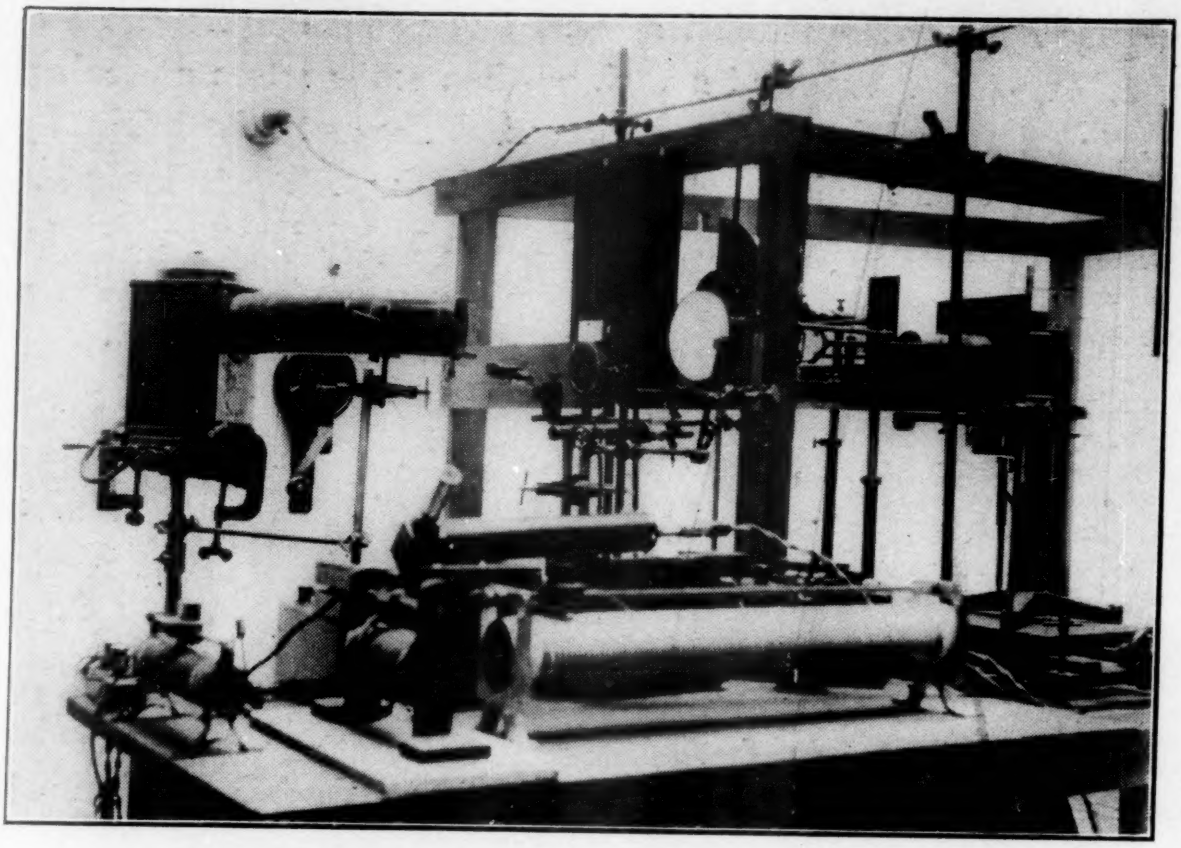


FIG. 6. Showing the apparatus assembled for work.

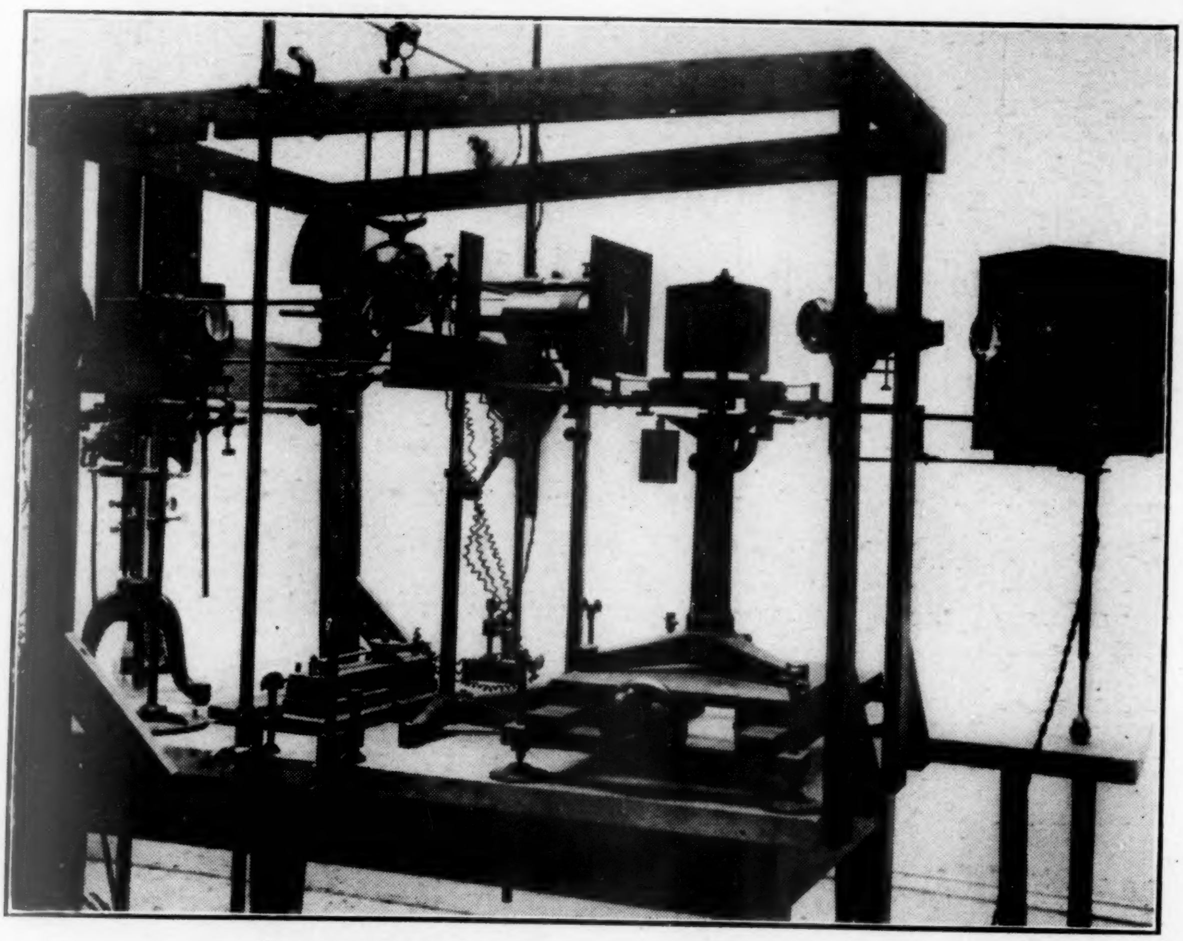


FIG. 7. Second view of apparatus.

III. EXPERIMENTAL.

It has been the purpose of the present investigation to study the effect of intensity of light, state of adaptation of the eye, and size of photometric field on the visibility curve. For this study the following provisions were needed: (1) An optics room which could be used both as a light and dark room; (2) provisions for a precise control and reproduction of the intensity of illumination of the light room; (3) An apparatus to furnish spectrum light of high intensity, free from impurities; (4) devices for reducing the intensity of the spectrum light continuously and by known amounts to very low values; (5) a photometric field suitable for use in either a light or dark room, one side of which is illuminated by a standard light, the other by the desired spectrum lights; (6) provisions for changing the visual angle subtended by the photometric field; (7) a device for the control of the fixation of this field sufficiently accurate to insure foveal stimulation when a field subtending a visual angle of 57 min. was used; and (8) apparatus for measuring the energy of the spectrum lights. The arrangement of the apparatus and the path of the beam of light to the eye are shown in Fig. 5. Photographs of the apparatus are given in Figs. 6 and 7. The greater part of the apparatus employed has been previously used in the Bryn Mawr College laboratory of Psychology and has already been described in considerable detail. (46, 47)

A. The Optics Room.

The apparatus was set up in a light room which could be converted into a fairly satisfactory dark room by means of a light-proof curtain. Conditions for complete dark adaptation were further provided for by enclosing both the source of light and the spectroscope, with its auxiliary apparatus for presenting the light to the eye, in light-proof compartments. The room was

16 feet long, 13 feet wide, and 12 feet high. The walls were painted a matte white and the floor a light gray. The room was provided with two windows on one side 3 x 6 feet and a skylight 12 x 9 feet. Beneath the skylight was a light well 8 feet deep at one end and 5 feet at the other. The walls of this light well were painted a matte white. Beneath the light well were swung two diffusion sashes of ground glass, each 12 x 45 feet. All of the light entering the room from the light well passed through these sashes. This served to diffuse the light and give an even illumination to the room. To provide for the ventilation of the room the sashes were dropped 11 inches below the opening of the light well.

In order to provide for the control and variation of the amount of daylight entering the room three sets of curtains were installed beneath the diffusion sashes, one broad light-proof curtain covering the entire ceiling of the room, the edges of which were enclosed to a depth of 1 foot in a light-tight boxing; and two sets of thin white curtains, one running lengthwise of the room and the other crosswise. The windows were also provided with light-proof curtains. Gross changes of illumination were made by means of the light-proof curtain; finer changes by means of the white curtains. All the curtains moved on wire supports to prevent sagging. The illumination was measured by means of a Macbeth illuminometer. The component of illumination received on its test plate was the same as that which fell upon the stimulus opening and its surrounding field. The metal screen in which the stimulus opening was cut was painted a matte black. It reflected approximately 2 per cent of the incident light. The photometric match between the daylight and the light from the lamp of the illuminometer was rendered easy to make by the insertion of appropriate colored filters of known coefficient of transmission. The spectroscope and the optical system were shielded from the light of the room as a source of impurity by the light-proof compartment in which they were enclosed. This was of course a very important reason for

enclosing the path of the beam from its source to the eye. The illumination of the room was kept constant for the work under light adaptation at 12.5 foot-candles, horizontal component.

B. The Apparatus

1. *The Source of Light.*

In the first half of this investigation a Nernst filament was used as the source of light. It is especially well suited for this purpose for several reasons: when properly seasoned it gives a light very constant both in intensity and composition; its flux of light is sufficiently great to permit of a direct measurement of the wave-lengths of the different parts of the spectrum and to provide the high intensities needed in making the photometric comparisons; its shape is well adapted for use with the slit of the spectroscope, *i.e.,* the shape is such as to make it possible to utilize for the illumination of the face of the prism a relatively large part of the light emitted. When in use the filament was placed as close as possible to the slit and directly in front of it. This requires that care be taken to keep the position of the filament in relation to the slit always the same, for the light which enters the spectroscope should always come from the same part of the filament, else changes both in its composition and intensity may occur due to temperature inequalities near the end of the filament. To insure this constancy of position a special mounting has been devised which provides for the removal and precise re-setting of the filament as occasion may require and gives the rigidity of support needed to prevent sagging or other displacement. The special features embodied in this mounting have been described in previous publications from this laboratory. The filament was operated on a 110-volt circuit in series with a ballast to compensate for variations in the resistance of the filament with change of temperature; two rheostats, one designed for gross changes of resistance; the other for the finer changes needed to correct for fluctuations of voltage in the operating circuit; and a Western ammeter graduated to 0.05 ampere. The

operating current was held constant at 0.7 ampere. The filament used was of the type designed to be operated on direct current.

For the second half of the work this type of filament could no longer be obtained. It had been superseded in the market by a filament made to be used with either direct or alternating currents. These filaments were found to have a very short life when operated at the desired amperage on direct current. A trial of various sources resulted in the choice of a tungsten lamp provided with a ribbon filament, made by the Nela Research Laboratories. This lamp proved to be very satisfactory. When operated at 14 amperes by a storage battery it was found to give approximately the same intensity of light as had been obtained with the Nernst filament. Also when properly seasoned it was found to give the desired constancy in composition and intensity of light and to be less troublesome to use than the Nernst filament.

Because of the construction of this lamp, the direct radiations from the filament could not be used satisfactorily for the illumination of the slit of the spectroscope. An image of the same size and shape as the filament was used instead. This image served to fill the slit completely and to give a uniform illumination of the face of the prism. The image was formed on the slit by two lenses L_1 and L_2 of the same focal length, 10 cm., one acting as a collimating, the other as a focussing lens. These lenses were mounted in proper alignment between the standard lamp and slit on a heavy metal bar continuous with the collimator arm of the spectroscope. The lamp and the lens L_1 were enclosed in a metal housing in the anterior wall of which a circular aperture 7 cm. in diameter was cut to allow the emergence of the collimated beam of light. This housing was painted a matte black both inside and out and was provided with light-proof ventilators. The focussing lens was mounted in front of this aperture at a distance of 8 cm. Because of the weight of the lamp with its auxiliary housing and lenses it was deemed advisable to provide additional support to relieve undue strain on the collimator arm. This was done by extending a rod from a position directly

under the center of the lamp-house to the table. On the lower end of the rod was a ball and socket caster. The caster traveling on the carefully smoothed surface of the table gave a minimum of impedance to the rotation of the collimator arm required in producing changes of wave-length. The lamp was connected in series with two rheostats and a Weston ammeter graduated to 0.2 ampere. As before one of these rheostats was used to cause gross changes of current, the other to produce the finer changes needed to correct for small fluctuations in the circuit.

2. *The Spectroscope.*

A diagramatic representation of the spectroscope is shown in Fig. 5. S_1 is the collimator slit; L_3 the collimator lens; P_r, the prism; L_4 the objective lens; S_2 the objective slit. The length of the collimator slit is 12 mm., the width 1.05 mm. This width of slit was necessary in order (1) that the energy measurements might be made with precision, and (2) that visibility determinations might be made at sufficiently high intensities. The analyzing slit S_2 is 0.415 mm. in width. By means of a special attachment its height can be varied in half millimeter steps. The total height of the slit without this attachment is 10.425 mm. When the apparatus was adjusted for making the energy measurements the full height of the slit was used in order to obtain high intensities. In the photometric work, a height of slit was chosen such that an image of the slit, focussed on the observer's eye, fell well within the pupil. In Fig. 5 is shown the arrangement by which the different heights of analyzing slit can be obtained and reproduced when desired. Two flat metal jaws M_1, and M_2, are beveled along their vertical sides in order that they may be moved up and down in the dovetailed guides G_1, and G_2, and so control the effective height of the slit S_2. A pin P in the upper metal jaw rests against one of a series of notches in a ratchet R. When the pin is in the first notch, the distance between the two jaws is 0.5 mm. As the pin is moved into each succeeding notch by rotating the ratchet, the distance between the jaws and therefore the effective

height of the slit is increased in half millimeter steps. A wire spring W keeps the pin pressed tightly against the notch.

The collimator and objective lenses L_3 and L_4 are Zeiss triple achromats, 60 mm. in diameter, with focal lengths of 180 and 240 mm. respectively. The prism Pr of hollow glass filled with carbon bisulphide, has a refracting angle of 60 deg. In order that all the wave-lengths falling on the objective slit might pass through the prism at minimum deviation, the spectroscope was fitted with a special attachment which is shown in Fig. 5. The following description of this device is quoted from a recent publication from this laboratory.(17) K in Fig. 5 "is a rod fastened to the prism table in such a position as to be continuous with the radius of the table which bisects the refracting angle of the prism; X and Y are two rods of equal length fastened at one end to the two arms of the spectroscope at points equidistant from the center of the prism table, and at the other to a collar Z, which is free to play back and forth along rod K. M is a micrometer screw with a graduated head which is used to move the collimator arm through the small angles needed to change the wave-length. Opposite this screw is a plunger working against a spring. The collimator arm is held between the screw and the plunger so that it responds to a movement of the screw in either direction. By this attachment the prism is always turned through half the angle traversed by the collimator arm in changing the wave-length. Therefore if the prism is set for minimum deviation for the D-line, there will also be minimum deviation for any other wave-length. That is when the prism is set for minimum deviation, the line bisecting the refracting angle of the prism also bisects the angle made by the incident and emergent rays; hence if in changing the wave-length the angle between the incident and emergent rays be changed a given amount by a movement of the collimator arm, the prism must be moved through half that angle in order that the line which bisects its refracting angle will also bisect the angle made by the incident and emergent rays."

The wave-length of the light falling on the analyzing slit is

determined by means of a small Hilger direct vision spectroscope calibrated for wave-length. Since the refractive index of carbon bisulphide varies somewhat with temperature, the wave-length was checked at frequent intervals during the taking of photometric readings to make sure that no change had occurred. In all quantitative work on retinal sensitivity it is very important that the light employed be as homogeneous as possible as to wave-length. In the work of this laboratory determinations made with and without provisions for absorbing impurities due to scattered light, internal reflections, etc., show differences large enough to be considered significant. In the present investigation the aim has been to obtain a degree of purity such that any portion of the spectrum used should show only one band when examined with a second spectroscope. In order to secure a high degree of purity of light the following precautions were observed. Stray light and internal reflections were eliminated as far as possible by enclosing all light sources, and by blackening possible surfaces that might reflect extraneous light into the refracted beam. To exclude the light of the room, the spectroscope with its auxiliary optical and photometric system was completely enclosed in a light-proof compartment. Even with these precautions, however, some impurities were nearly always found, chiefly those due to reflections from the surfaces of the lenses. These were absorbed by very thin gelatine filters, carefully selected with reference to the bands to be eliminated. The gelatine filters were held in place over the objective slit by small clips fastened on either side of the plate containing the slit. The filters were used both for the radiometric measurements and for the photometric determinations.

3. *Apparatus for Reducing the Intensity of the Spectrum Light.*

Obviously means of making both gross and fine changes of intensity are needed in a study of this type. Gross changes were needed to cover the wide ranges of intensity of light employed, the maximum representing a relation of 75,000: 1; and finer changes, to make the photometric settings with the

delicacy and precision required to detect small changes in the eye's selectiveness of response both to wave-length and intensity. For making the gross changes, gelatine filters and a specially prepared set of sectored discs were used; for making the finer changes, a pair of gelatine wedges so designed as to give minutely graded changes of intensity which were uniform throughout the cross section of the beam of light.

The sectored discs. Instead of using pairs of discs with a variable open sector the value of which, particularly when small, would have been difficult to measure with any means available during the course of the work, eight separate discs with fixed open sectors were used interchangeably. These were constructed to give transmission values of approximately $^1/_2$, $^1/_4$, $^1/_8$, $^1/_{16}$, *etc.* The values of the open sectors were measured on a micrometer comparator, and the exact transmissions computed from the simple law of the disc. The values of the sectors were 179.5, 88.7, 44.08, 21.8, 11.75, 5.683, 2.717, and 1.333 deg.; the transmissions were 49.9, 24.6, 12.2, 6.1, 3.3, 1.6, 0.75, and 0.37 per cent. The discs were rotated across the beam of light by means of a motor suspended by three coiled springs so attached as to form a three-point support. These springs served both to hold the motor in position and to absorb all disturbing vibrations.

The gelatine filters. Still further reduction was provided for by four gelatine filters whose transmissions were again approximately $^1/_2$, $^1/_4$, $^1/_8$ and $^1/_{16}$. These filters which were supplied by the Eastman Kodak Company, are called "Neutral Tint Optical Filters." They are found, however, to have transmission values which vary slightly from wave-length to wave-length. Since in this investigation these filters were to be used with monochromatic light, it was deemed advisable to apply corrections for selectiveness of transmission. Calibration curves determined spectrophotometrically were therefore obtained from the Eastman Kodak Company, and the densities of the filters for the particular wave-lengths used in this investigation were

computed from these curves. The transmission of each filter was calculated by the formula, density = log. $\frac{1}{\text{transmission}}$. To this result was applied in each case the appropriate factor to correct for selectiveness of transmission.

The double wedges. As already stated, the purpose of the wedges was to make the small variations of intensity between those given by the possible combinations of sectors and filters, that were needed for adjusting the spectrum lights to a photometric balance with the standard light. Obviously, two conditions are essential in making these variations: a means must be had of making very small changes of intensity; and the method employed must insure a completely uniform reduction throughout the cross section of the beam of light. A single wedge such as is ordinarily employed may meet the first of these requirements but not the second. Even when placed in front of the slit, no matter how fine the gradation in density, there is always a slight difference between the opposite edges of the portion of the wedge used. The double wedge device has been designed to obviate this difficulty. The two wedges were made according to specification and calibrated in the laboratories of the Eastman Kodak Company. Like the filters, they are made of gelatine stained to give approximate neutrality and mounted between oblong plates of glass. The wedges are identical in size and shape, each being 180 mm. x 20 mm. and constructed to include the same range of transmission. They are mounted parallel to each other in holders which are operated by a rack and pinion device. This device is so constructed that when the pinion is turned, one rack is engaged by the cogs at the top and the other by the cogs at the bottom. The holders to which these racks are attached are thus caused to move by equal amounts in opposite directions. Each wedge can thus be made to travel in front of the other through a path equal, if need be, to twice the length of one wedge, that is, from a position of juxtaposition at the thin end of the wedge to a position of juxtaposition at the thick end. Since

the density gradients of the two wedges are identical and the wedges move in opposite directions, it is obvious that the resulting density will be the same from point to point throughout the overlapping section. A consideration of the range of movement shows further that a series of densities may be obtained varying by minute amounts from the sum of the minimum densities of both wedges, through the sum of the minimum of one and the maximum of the other, to the sum of the maximum of both. The density in this case also equals $\log \dfrac{1}{\text{transmission}}$.

The wedges used in this investigation have a transmission ranging from 81.5 to 31 per cent. No calibration for selectiveness of transmission was thought to be necessary for them because it was found from inspection of the data for the gelatine filters that the errors due to this factor are negligible for transmissions greater than 25 per cent. When in position for use the wedges were mounted directly in front of the objective slit of the spectroscope. So located they were within the light-proof compartment which encloses the spectroscope, well beyond the reach of the observer. In order that the transmission of the wedges might be varied by the observer while making the photometric match, the pinion wheel is connected by means of a long rod which extends through the front wall of the compartment to a milled head within easy reach. The milled head is connected in turn to a dial through a series of gears. The ratio of these gears is such that the distance through which the wedges are moved can be read directly on a graduated scale on the beveled edge of the dial. The relation of this scale to the density gradient of the wedges is such that 1 mm. corresponds to a change of 0.7 per cent or less in the intensity of the light transmitted. Since the scale can be set and read to quarter mm. changes of less than 0.2 per cent in the amount of light transmitted are provided for. In making a photometric match between the white and colored fields the observer was thus able by moving the wedges back and forth to vary the amount of light in the field by less

than just noticeable amounts until a match was obtained. The possibility of thus making fine adjustments of the intensity of light while viewing the photometric field is obviously of great assistance in making the judgment and adds greatly to the precision and delicacy of the determination.

4. The Photometric Field and Device for Control of Fixation.

The photometric field employed was circular in form. One half of this field was filled with the standard light, the other half with spectrum light. The standard light was reflected from a metal plate one edge of which bisected the photometric field vertically. This plate was coated with magnesium oxide deposited from the burning metal. In order to avoid the appearance of a dark line between the two halves of the field the edge of the plate was ground very thin.

The method of presenting the spectrum light to the eye may be described as follows: The light emerging from the objective slit was collimated by the lens L_5 and focussed on the eye of the observer by the lens L_6. This in accord with a well known optical principle causes the lens L_6 to appear to be uniformly filled with light. The colored field thus produced was limited to the size desired by a metal screen containing a circular aperture, placed between the focussing lens and the eye of the observer. The circular aperture was carefully centered in the beam of light emerging from the lens L_6. Two sizes of field were used, a foveal size subtending an angle of 57 min. at the eye and an extrafoveal size subtending an angle of 4 deg. 49 min. In order to obtain this value of visual angle in the experiments with the foveal size of field, a lens L_6 with a focal length of approximately 50 cm. was used; the screen Sc was placed 10 cm. in front of the lens or at a distance 40 cm. from the eye; and the circular aperture in the screen was made 6.66 mm. in diameter. In the series with an extrafoveal size of field a lens with a focal length of approximately 25 cm. was used to focus the light on the eye; the screen was placed at a distance of 15 cm. from the eye; and the aperture was 12.62 mm. in diameter. In order

that the amount of light entering the eye should not vary with changes in the size of pupil, it is necessary that the cross-section of the beam of light where it enters the eye shall be smaller than the smallest size of pupil. This can be accomplished either by the use of an artificial pupil or by focussing the light on the eye. The latter of these procedures which is in general very much superior to the former, is made possible in this investigation by the method used in presenting the light to the eye. This point, however, is of importance chiefly in specifying the level of intensity at which the determinations were made. It is of no importance as affecting the shape of the visibility curve, for all the determinations which furnish the data for any given curve are made at the same level of intensity, state of accomodation, etc., and therefore presumably with the same size of pupil.

In the method used for presenting the light to the eye, the light from the objective slit, it will be noted, is collimated by the lens L_5 and focussed on the eye by the lens L_6. An image of the slit is thus formed in the pupil of the eye. By the choice of the proper length of slit and ratio of diopter value or focal length of the collimating and focussing lenses, this image can be made smaller than the minimum size of pupil. The length of objective slit selected to satisfy these conditions was 1 mm. for the foveal size of field, and 2 mm. for the extrafoveal size of field. The collimating lens L_3 was of the same focal length for both sizes of field. Since the focal lengths of the lens L_6 were respectively 50 and 25 cm., the relations of sizes of image and size of slit were in the two cases 30:50 and 30:25. In order to determine accurately the size of these images, they were photographed on a plate placed in the plane of pupil, and the dimensions of the photographed images were measured with a micrometer comparator. The dimensions of the two images were found to be 1.3244 x 3.084 mm. and 0.637 x 2.972 mm. respectively. Accurate data as to their dimensions were needed in computing in terms of energy the density of light at the pupil of the eye.

To insure that the eye be held steadily in position to receive

the image of the objective slit always in the same place in the pupil, a mouth bit was used in which an impression of the observer's teeth had previously been made and hardened in wax. For convenience of adjustment, the mouth bit was mounted on a support which could be shifted by a screw motion backwards and forwards and up and down. The right and left adjustment, for which so fine a control was not necessary, was obtained by moving the tripod support on which the mouth bit was mounted. When the mouth bit had been carefully adjusted to the position which caused the image of the slit to fall in the center of the pupil and the stimulus opening to be uniformly filled with light, the tripod was securely clamped to the table. With these controls the eye could be held in a fixed position throughout a given series of observations or be returned to this position from time to time. In addition both an objective and subjective check on the correctness of the relation of the eye to the optical system could be applied at any time.

One of the mooted points with regard to the Purkinje phenomenon is whether it takes place in the fovea. It will be recalled from the historical section that several investigators claim that its occurrence in the fovea is an artifact due to the failure of the observer to control his fixation. Apparently great difficulty has been experienced in providing satisfactory devices for the control of fixation at the very low levels of intensity at which the changes in relative sensitivity are the most apt to occur. To overcome this difficulty the following method was devised. Four points were located just within the margins of the Mariotte spot, two in the vertical and two in the horizontal meridan. These points were located with the eye fixating a point at the center of the photometric field under an intensity of illumination for which such a control is satisfactory. The points were then covered with luminous paint. Being just within the blind spot they are invisible so long as the eye holds its proper fixation. A slight movement in any direction, however, is indicated by the appearance of one or more of the points. This device provides not only an extremely sensitive means of detecting inaccuracies

of fixation, but also detectors which are invisible during the process of fixation. That is, no possible influence can be exerted by them on the use of the eye as a means of balancing the luminosities of the two halves of the field under observation. Previous investigators, it will be remembered, have attempted to control fixation at low illuminations by placing a luminous point at the center of the photometric field. The presence of an alien luminosity at the central part of the common margins of the two fields is not only disturbing to the sensory reaction and the judgment of this reaction but it affords an insensitive means for detecting errors in fixation. That is, the observer is aware of movement of the eye only through an apparent movement of the fixation object or a decrease in the clearness with which it is seen, both of which come only with comparatively large lapses of fixation.

In the use of the blind spot method some interesting tendencies toward errors of fixation were revealed. For example, at high intensities of illumination of the photometric field, the four luminous points were always found to disappear when the center of the field was fixated, *i.e.*, at these intensities the ordinary means of control sufficed within the limits of precision furnished by the blind spot method used as a check. At intensities of 0.2 and less, however, particularly with a foveal size of field and dark adaptation, this was found not to be the case. Under these conditions the customary controls of fixation were found to be far from adequate. In addition then to serving as a powerful corrective of involuntary movements the blind spot method indicates to the observer when a determination has been made with a faulty fixation. In compiling the data for this study all such determinations have been discarded. The ability to make this selection of data has been an indispensable aid in arriving at a conclusion with regard to whether the Purkinje phenomenon occurs in foveal vision.

5. *Apparatus for the Illumination of the Standard Field.*

The problem of the illumination of the standard field presented the following features: (1) A definite small area within the

light-proof compartment had to be illuminated uniformly in such a way as to produce a minimum of stray or scattered light. (2) No light could be allowed to escape into the room either from the lamp used as source or from the transmitting system. (3) A wide range of variation of intensity of light had to be provided for without change of size or shape of the illuminated area, the evenness of its illumination, or the composition of the light. Also there was need that the apparatus be more compact in form and more convenient to operate than the usual photometric equipment. The method of securing an evenly illuminated area of a definite size and shape and of varying the intensity of illumination without changing the composition of the light or the size, shape and evenness of illumination of this area, was similar to that devised by Ferree and Rand for the illumination of acuity objects and test charts. A brief statement of the principle is contained in the following quotation: (48) "While it is difficult, if not impossible to illuminate uniformly a surface of any considerable size directly or indirectly from one or more sources of light, it is not especially difficult to illuminate evenly a surface of small size by devices which are feasible, and to project the magnified image of this surface on a larger one. . . . A small aperture of the desired shape and dimensions is illuminated uniformly and its magnified image is projected on the surface to be illuminated. This use of an image for the purpose of illumination paves the way also for the solution of the second problem, namely, the obtaining of finely graded changes of intensity without change in color of light. That is, any variation in the size of aperture of the projection lens employed changes the intensity of the light in the image formed without altering the evenness of distribution of light or changing the size or shape of the image. A convenient means of producing regular and known changes in the size of the aperture is an iris diaphragm placed as near as possible to the front or back surface of the lens."

The projection apparatus used in this study consisted of a light-tight metal lamp housing lined with sand blasted opal glass, except for a small aperture 1 x 1 cm. located in a suitable position

in the front wall of the housing. This aperture was illuminated by light diffusely reflected from the lining of the lamp house. The source of light was a Mazda lamp. The lamp was screwed into a socket in the base of the lamp house at such a distance below the aperture to be illuminated that the component of direct illumination was small. In order further to insure an even illumination of the aperture it was covered with a thin plate of single-thick optical glass ground on both sides. The lens used to form an image of this aperture on the photometric field was mounted in a projection tube attached to the front wall of the lamp house. In order to prevent the escape of stray light into the room this tube was made long enough to extend from the lamp house to a point well within the compartment containing the spectroscope with its auxiliary apparatus and the photometric field. It was attached to the lamp house in such a position that the axis of the lens passed through the center of the aperture to be imaged. Directly in front of the lens and as close to it as possible was mounted the iris diaphragm used for the variation of intensity. At a suitable point in the milled head used to operate the diaphragm was attached a pointer. As the diaphragm was opened and closed this pointer traveled over a translucent scale graduated in mm. divisions. In order that this scale might be read without an auxiliary source of illumination, it was fastened over a slot in the projection tube. The size of the luminous image projected by this apparatus was 2.1 x 2.1 cm. In order to insure a clean cut edge between the standard and comparison fields, the image was allowed to extend slightly beyond the beveled edge of the plate coated with magnesium oxide on which it was projected.

Before the lamp house was permanently mounted in position the millimeter scale was calibrated in meter candles. This calibration was accomplished as follows: The lamp house was mounted on photometer bar at such a distance from the Lummer-Brodhun photometer head that the image of the illuminated aperture was focussed upon the test plate of the photometer head. The illumination in meter candles given by the lamp house was determined for each point of the scale. In order to obtain the

full range of intensities desired it was found to be necessary to use two lamps, one to cover the lower part of this range, the other the upper part. The wattages of these two lamps were respectively 100 and 250. The scale was calibrated for both lamps. The range for the smaller lamp extended from 0.6284 to 23.59 m.c.; for the larger from 21.1 to 95.4 m.c.

In order to obtain intensities lower than 0.6 m.c. filters were used. These filters were placed in holders attached to the end of the projection tube. By the use of two filters singly or in combination, in connection with the iris diaphragm, it was found possible to obtain any intensity between 95.4 m.c. and 0.0063 m.c. The lamps were operated on a 110 volt circuit in series with a Weston ammeter graduated to 0.05 ampere, and a rheostat. In order to be able to make the fine changes in resistance needed to compensate for small fluctuations in voltage, the rheostat was of the rotating coil type.

As already stated one of the reasons for using a focussed image to illuminate the standard photometric field was to render it possible to make changes in the intensity of light on this field entirely independent of the illumination of the room. Visibility determinations could thus be made at any level of intensity with the observer in a state of complete dark adaption or in any state of light adaption that was desired. In the photograph shown in Figure 6 the lamp house is shown without the extension of the projection tube. With this extension in place and light-proofed where needed with black cloth, the magnesium oxide surface serving as the standard photometric field was completely shielded from the light in the room with the exception of the small amount that might come through the stimulus opening. As a precaution against light coming through this opening when working in the light room, the observations were made through a dark tube extending from the eye to the screen Sc. In order to interfere as little as possible with the state of light adaption in these cases the observations were made in a series of quick judgments with the eye exposed to the light of the room between judgments.

C. Method of Working

1. The Radiometric Measurements.

The apparatus used in measuring the energy of the spectrum lights consisted of a bismuth-silver thermopile, a sensitive galvanometer of the Thompson type designed expressly for use with this thermopile, and auxiliary calibration apparatus for the thermopile and the galvanometer. These instruments were constructed by W. W. Coblentz of the Radiometric Division of the Bureau of Standards. For a detailed description of the complete radiometric equipment the reader is referred to previous articles published from this laboratory. (47, 49)

The procedure used in making the energy measurements may be described as follows: " The thermopile to be used was placed in position immediately behind the slit and a blackened aluminum shutter was interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer was tested by means of a special device provided for this purpose in the construction of the galvanometer. With regard to this procedure it may be pointed out that the current sensitivity of the galvanometer varies with the period or time of the single swing of its needle system. Since it is not possible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a correction factor determined at each sitting. (For a detailed description of the method of determing this factor, see Psychol. Rev. Monog., 1917, 24, No. 2, pp. 60–65.)

" The thermopile was next connected with the galvanometer and the light allowed to fall on its receiving surface until a temperature equilibrium was reached (ca. 3 sec. for our thermopile). The deflections were read by means of the telescope and scale and the readings were corrected to standard sensitivity by means of the factor previously determined. The final step in the process of measuring was the calibration of the apparatus, *i.e.*, the value of

1 mm. of deflection in radiometric units was determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiations from which is already known, had to be employed. The standard used by us was a carbon lamp specially seasoned and prepared for the purpose by W. W. Coblentz. This lamp was placed on a photometer bar 2 meters from the thermopile and operated at one of the intensities for which the calibration was made, in our case 0.40 ampere. The thermopile was exposed to its radiations with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection was recorded. From the deflections obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, was computed from the known amount falling on the surface of the thermopile. Having the factor expressing the radiation sensitivity of the apparatus, the deflections produced by the wave-lengths of light measured were readily converted into energy units." (49)

The writer is indebted to Dr. Rand for making the energy measurements needed in the present investigation. In one series of these measurements, the radiation sensitivity of the thermopile was calculated from the following data. The energy value of the radiation from the standard lamp at a distance of 2 m. operated at 0.40 ampere was 90.7×10^{-8} watt per sq. mm. of received surface. The deflection of the galvanometer produced by this intensity of radiation falling on the same area of receiving surface as was used in measuring the lights employed as stimuli when corrected (a) to a standard sensitivity of 1×10^{-10} ampere per sq. mm. of deflection and (b) for the absorbtion of the glass cover of the thermopile, was 366 mm. The area of the surface exposed was 4.326 sq. mm. The sensitivity of the instrument for this area of receiving surface was, therefore, 1.072×10^{-8} watt per millimeter deflection. By means of this factor the galvanometer readings produced by the different wave-lengths of light were readily converted into the energy values of the light falling on the receiving surface of the thermopile.

In order to obtain values sufficiently great to be measured with

precision, the energy determinations were made at the objective slit. Although not necessary it is desirable in visibility determinations to know also the energy values of the light entering the eye. The energy which can be obtained at the eye is sufficiently great in the long wave-length end of the spectrum to be measured directly with precision. From the comparative values of a band in the red, measured at the objective slit and again at the eye, a factor is determined which represents for all wave-lengths the reduction of the light from the objective slit to the eye. This factor was computed in a given case, for example, from the following data: energy falling on the thermopile at the eye, 243.2×10^{-8} watt; at the objective slit 2592.0×10^{-8} watt. The ratio of these two values gives a correction factor of 0.0938. The value 243.2×10^{-8} watt was, however, obtained for an exposed area of pile at the eye equal to 8.79 sq. mm. To obtain energy *per sq. mm.* at the eye, therefore, the readings at the objective slit must be multiplied by $\frac{0.0938}{8.79}$ or 0.01067.

From these values of energy density at the eye, the energy density in the stimulus opening, and the total energy entering the eye, may be obtained by multipliying by the proper factors. Values for the total energy at the eye are given in Table VIII.

TABLE VIII

Wave-length	Energy at Eye in Watts x 10^{-10} Extrafoveal Series	Energy at Eye in Watts x 10^{-10} Foveal Series	Wave-length	Energy at Eye in Watts x 10^{-10} Extrafoveal Series	Energy at Eye in Watts x 10^{-10} Foveal Series
454 mμ	99.87	7.296	557 mμ	172.2	17.57
470	129.6	9.702	580	474.7	58.05
485	151.7	13.87	597.5	1116.4	153.7
502.5	178.2	17.27	619	1399.4	201.4
522.5	191.6	19.42	643	4101.6	547.7
540	218.8	22.18	697	4169.8	776.9

2. *The Determination of Relative Visibility.*

It has been the purpose of the present investigation to determine the effect of three important factors: intensity of light, state of adaptation of the eye, and size of the photometric field, on the shape of the visibility curve. The investigation has been made under the following conditions: (1) In order that the effect

of the three factors may be studied under comparable conditions, the same eye and the same experimental conditions have been used throughout. (2) The determinations of relative visibility have been made by the equality of brightness method of photometry. The position has been taken in this study that determinations by the flicker method of photometry, because of the short exposures used, do not represent true visibility, *i.e.,* visibility for the conditions under which the eye is ordinarily used. (3) The energy of the lights used has been measured directly. A great deal of uncertainty has been introduced in much of the previous work by the attempt to calculate or otherwise determine the energy of the lights employed from measurements made on spectra obtained from a different source and under different spectroscopic conditions. (4) The spectrum lights employed have been examined with a second spectroscope for alien wave-lengths. When found these wave-lengths have been eliminated by means of specially selected gelatine filters. With two exceptions (Ferree and Rand, and Gibson and Tyndall) this precaution, which is very important in determinations of relative sensitivity, has not been taken in the work of previous investigators.

For dark adaption, extrafoveal size of field, visibility curves were determined at the following levels of intensity, 75, 40, 20, 10, 5, 2, 0.2, 0.02, 0.01, 0.002, and 0.001 m.c; for dark adaptation, foveal size of field, at 75, 40, 20, 10, 5, 2, 1, 0.2, 0.1, 0.05, 0.02 and 0.01 m.c. In the two corresponding series for light adaptation the two lowest intensities were omitted in each case, namely, 0.002, and 0.001 for the extrafoveal size of field and 0.02 and 0.01 for the foveal size of field. These intensities were omitted because they were either below the threshold or very close to it under the conditions imposed by high adaptation at the given intensity. That is, in choosing the range of intensities to be used, the intention was to have the lower limit of the range as close to the threshold as it was possible for photometric determinations to be made with an acceptable degree of precision. It was also planned to have the steps small enough to show every significant change in the shape of the curve.

For the greatest number of the intensities used determinations were made at 12 points in the spectrum: 697, 643, 619, 597.5, 580, 557, 540, 522.5, 502,5, 485, 470 and 454 mμ. A few of the higher intensities could not be obtained at 485, 470, and 454 mμ. Determinations for those intensities could not be made therefore at these points.

Before making the determinations the eye was presensitized to each condition of illumination by a period of adaptation of thirty minutes in the dark room and fifteen minutes in the light room. In preliminary work these periods were found to be sufficiently long to give constancy of result. The time of exposure for making the photometric judgment was two seconds. For timing these periods a seconds clock connected in series with two dry cells, a key, and telegraph sounder, was used. Because of the difficulty of making the photometric judgment in the presence of such great color differences as were present, several months were spent in practice before final determinations were made. In the practice work judgments were made, under light and dark adaptation and at several levels of intensity, at all the points in the spectrum which were later to be used in the investigation proper. The observer used in this research has been found to have normal vision in every respect. Her color vision has been tested at the Bureau of Standards by means of the Stilling charts and Nagel's anomoloscope. She has moreover acted as observer in a number of researches in vision; for example, her color fields and blind spot have been mapped, her achromatic and chromatic thresholds for the central retina have been determined for a number of points in the spectrum, her acuity and speed of vision have been determined at a number of intensities of light, *etc.* No abnormalities have been found in the results of any of the investigations.

IV. RESULTS

In Tables IX–XII are given in logarithmic terms the amounts of energy required to match photometrically each of the intensities of light used as standard. These values represent for each of the lights employed the total amount of energy entering the eye. It is desirable sometimes to know in addition the energy density or flux per square millimeter at the stimulus opening and at the pupil of the eye. Values representing those densities respectively can be obtained by deducting from the figures given in Tables IX–XII 1.2382 and 0.61066 respectively for the foveal sizes of field, and 1.7960 and 0.27646 for the extrafoveal sizes. The values given in these tables were calculated from the experimental data as follows: to the logarithm of the energy at a given wave-length were added the logarithms of the transmission of the rotating sector, the double wedges, and the filters, used in reducing the light to the desired intensity. In addition a correction was

TABLE IX

Showing in logarithmic terms the amounts of energy per second[1] of spectrum lights required to match each of the photometric standards under light adaptation; size of field 57 min. In deriving these values 1×10^{-14} watt is taken as a unit.

Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	1 m.c.	0.2 m.c.	0.01 m.c.	0.05 m.c.
454 $m\mu$					4.70	4.27	3.85	3.22	3.23	2.90
470				4.83	4.40	3.94	3.51	2.89	2.88	2.52
485			5.05	4.77	4.41	3.91	3.64	2.85	2.75	2.44
502.5	4.99	4.81	4.49	4.16	3.81	3.34	3.14	2.53	2.46	2.17
522.5	4.76	4.51	4.23	3.85	3.54	3.04	2.75	2.23	2.12	1.82
540	4.51	4.28	4.01	3.66	3.32	2.88	2.60	1.88	1.76	1.54
557	4.506	4.22	3.93	3.63	3.31	2.84	2.57	1.85	1.73	1.51
580	4.57	4.30	4.01	3.66	3.38	2.88	2.59	1.93	1.80	1.52
597.5	4.79	4.53	4.24	3.90	3.54	2.99	2.71	2.06	1.89	1.66
619	5.14	4.90	4.62	4.28	3.73	3.25	3.00	2.26	2.15	1.95
643	5.65	5.38	5.15	4.77	4.15	3.61	3.32	2.65	2.53	2.34
697		6.62	6.28	5.99	5.38	4.68	4.36	3.87	3.47	3.28

[1] The values given in this and the three following tables represent the total amounts of energy entering the eye. To obtain corresponding expressions for the densities or flux per sq. mm. at the stimulus opening and at the pupil of the eye, 1.7960 and 0.27646 respectively must be subtracted from these values for the extrafoveal size of field, and 1.2382 and 0.61066 for the foveal size.

made when needed for the selective absorption of the filters. An example of this calculation for a given set of conditions, wave-length 597.5 mμ, light adaption, and foveal size of field, is given below.

+ 6.1845	log. of energy[1] of spectrum at 597.5 mμ.
— 1.801728	log. of transmission of sector No. 6.
— 0.24	log. of transmission of wedge at scale reading of 7.05 cm.
— 0.61	log. of transmission of filter.
+ 0.012	correction for selectivity of filter at 597.5mμ.
+ 3.544772	log. of energy[1] required to give 5 m.c. at 597.5 mμ.

[1] 1×10^{-14} watt is taken as the unit.

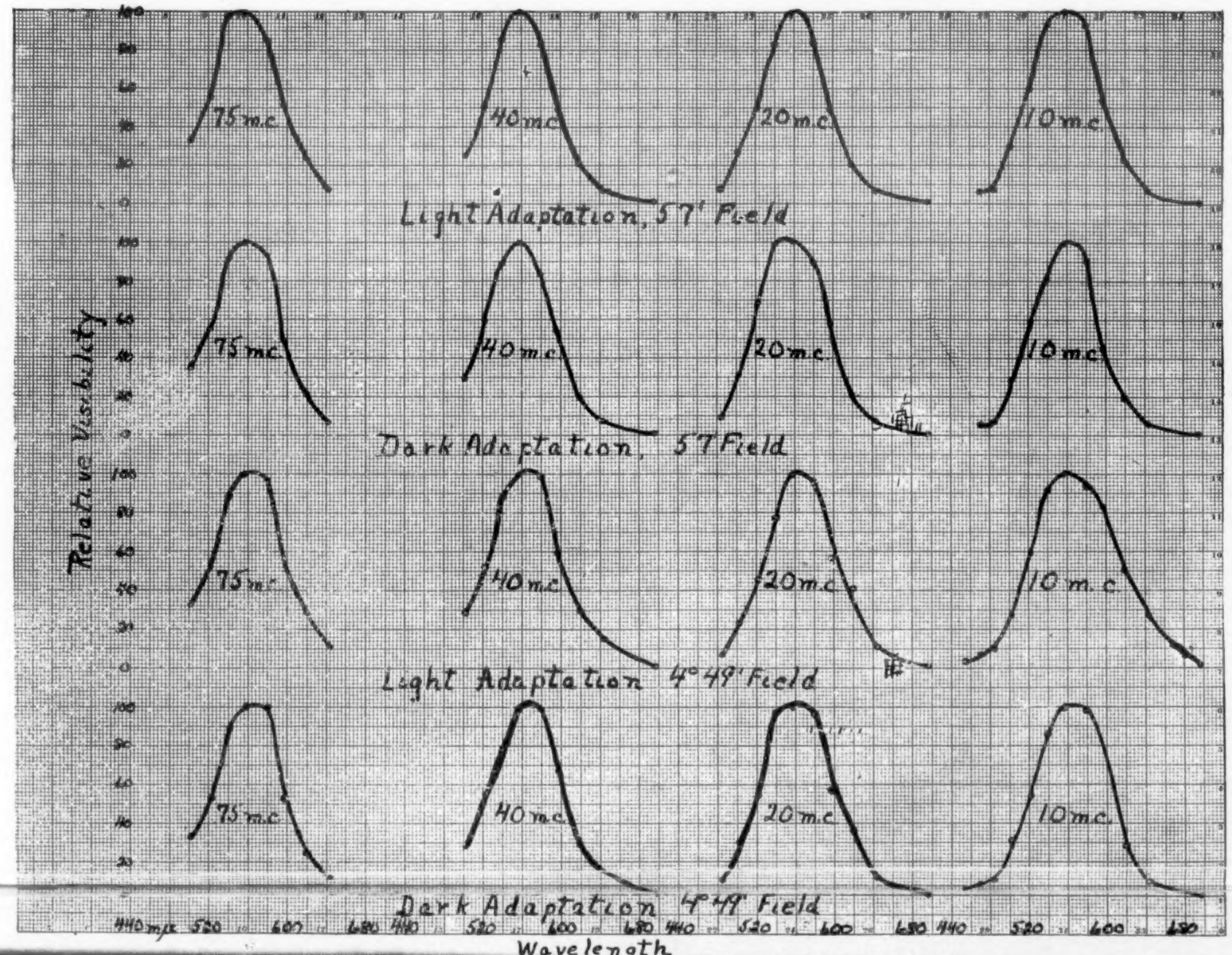
From the amounts of energy corresponding to the values given in Tables IX–XII the relative visibilities at the different points in the spectrum are calculated. These visibilities are taken as the reciprocals of the energies of light required to match the photometric standard at the various intensities. For convenience of comparison and reproduction they have been reduced to a scale in which 100 is chosen to represent the maximum value of the reciprocal. So graded the relative values of the reciprocals are shown in Tables XIII–XVI. Curves plotted from these values are given in Fig. 8. In this figure all of the curves are assembled on one chart to show in a general way the effect of the various conditions and factors studied. To bring out special features

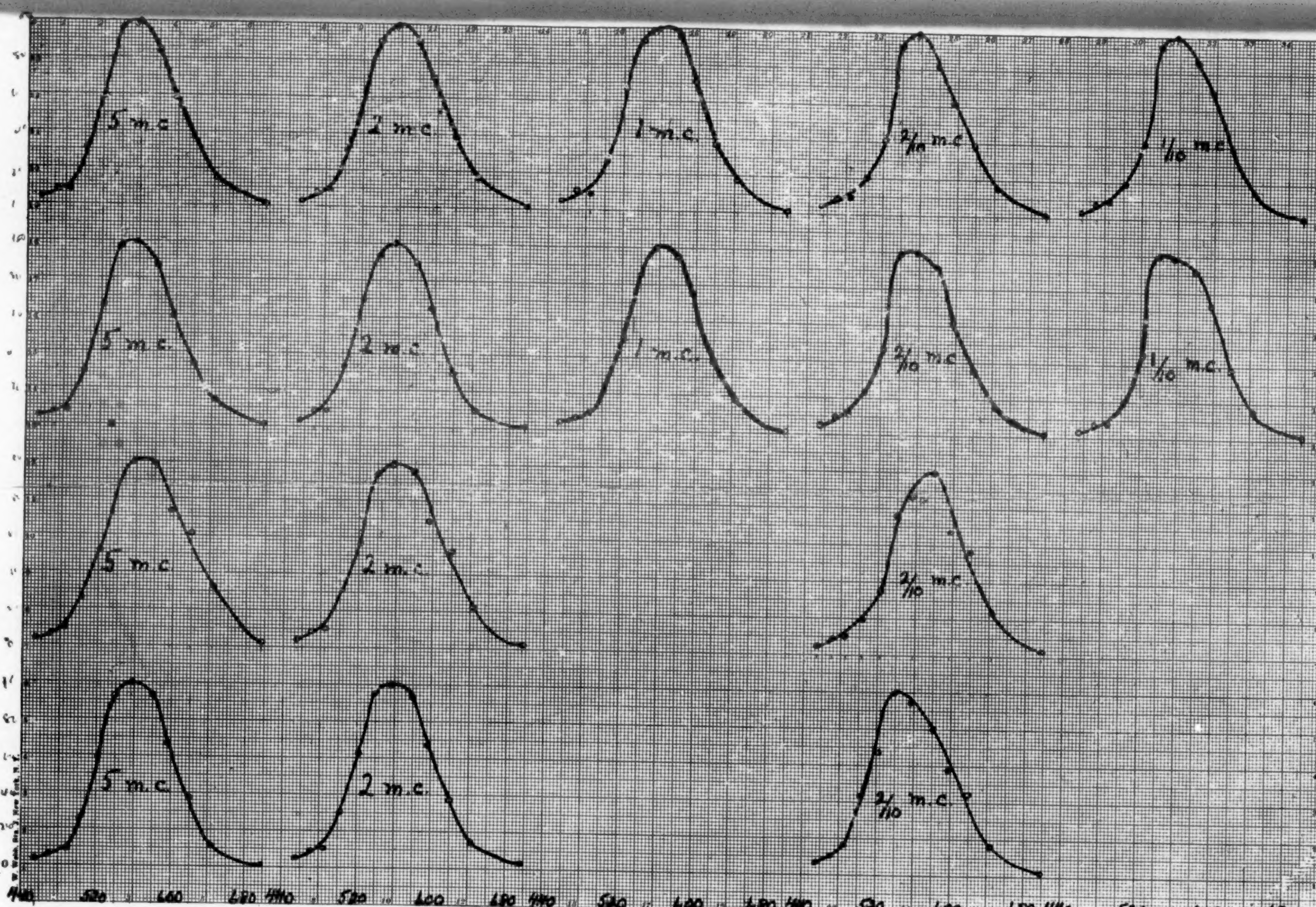
TABLE X

Showing in logarithmic terms the amounts of energy per second of spectrum lights required to match each of the photometric standards under dark adaptation; size of field 57 min. In deriving these values 1×10^{-14} watt is taken as a unit.

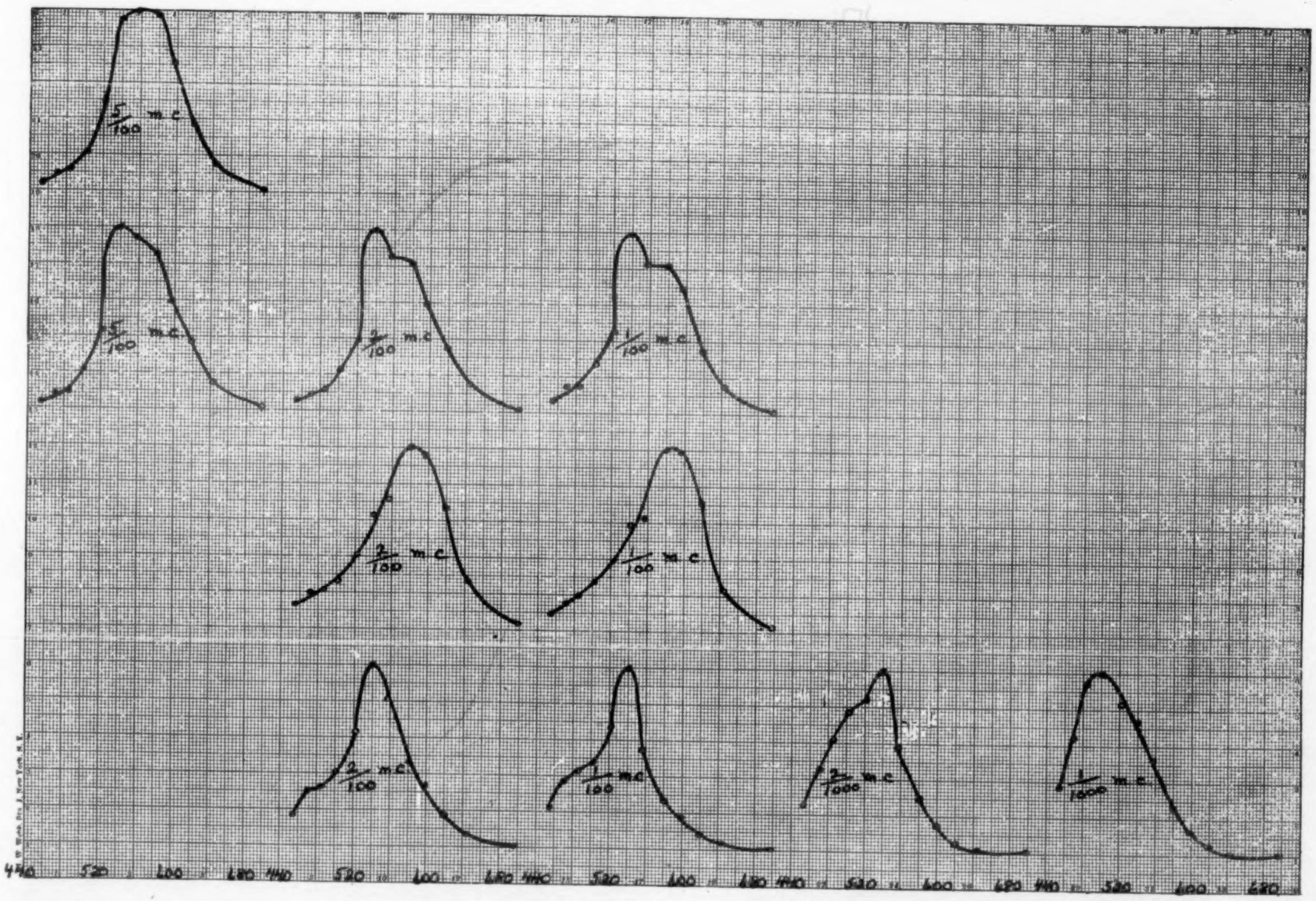
Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	1 m.c.	0.2 m.c.	0.1 m.c.	0.05 m.c.	0.02 m.c.	0.001 m.c.
454 mμ					4.77	4.34	3.94	3.14	3.05	2.80	2.15	1.94
470				4.85	4.44	3.94	3.72	2.85	2.75	2.46	1.95	1.58
485			5.05	4.79	4.42	3.95	3.55	2.83	2.71	2.39	1.86	1.59
502.5	4.96	4.75	4.51	4.16	3.86	3.36	3.20	2.49	2.32	2.03	1.56	1.32
522.5	4.75	4.45	4.28	3.84	3.51	3.05	2.83	2.24	1.94	1.73	1.32	1.09
540	4.53	4.28	4.02	3.70	3.34	2.92	2.61	1.86	1.58	1.36	0.91	0.75
557	4.49	4.22	4.01	3.61	3.33	2.89	2.54	1.859	1.61	1.39	0.98	0.83
580	4.53	4.30	4.06	3.65	3.39	2.94	2.56	1.90	1.64	1.43	1.00	0.83
597.5	4.81	4.58	4.26	3.95	3.55	3.08	2.66	2.08	1.78	1.59	1.14	0.91
619	5.16	4.93	4.70	4.33	3.80	3.42	2.95	2.31	2.05	1.80	1.27	1.20
643	5.68	5.37	5.13	4.84	4.18	3.90	3.30	2.67	2.42	2.20	1.75	1.57
697		6.66	6.22	5.97	5.36	4.95	4.43	3.74	3.55	3.17	2.74	2.56

FIG. 8. Showing visibility curves for a number of intensities of spectrum lights, determined under the following conditions: light adaptation, foveal size of field; dark adaptation, foveal size of field; light adaptation, extra-foveal size of field; dark adaptation, extrafoveal size of field.





5 m.c.
2 m.c.
1 m.c.
2/10 m.c.
1/10 m.c.
440
520
600
680



5/100 m.c
5/100 m.c
2/100 m.c
1/100 m.c
2/100 m.c
1/100 m.c
2/100 m.c
1/100 m.c
2/1000 m.c
1/1000 m.c
440 520 600 680 440 520 600 680 440 520 600 680 440 520 600 680 440 520 600 680

TABLE XI

Showing in logarithmic terms the amounts of energy per second of spectrum lights required to match each of the photometric standards under light adaptation; size of field 4° 49′. In deriving these values 1×10^{-14} watt is taken as a unit.

Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	0.2 m.c.	0.02 m.c.	0.01 m.c.
454 mμ				5.87	5.55	5.12	4.06	3.03	2.85
470				5.61	5.34	4.83	3.81	2.83	2.60
485			5.92	5.54	5.22	4.76	3.75	2.79	2.50
502.5	5.93	5.72	5.40	5.00	4.74	4.28	3.47	2.69	2.35
522.5	5.73	5.46	5.12	4.66	4.43	4.02	3.20	2.50	2.20
540	5.50	5.24	4.90	4.48	4.23	3.79	2.87	2.32	2.03
557	5.45	5.18	4.78	4.44	4.15	3.77	2.81	2.26	2.00
580	5.46	5.19	4.80	4.47	4.15	3.78	2.75	2.11	1.79
597	5.71	5.41	5.03	4.52	4.28	3.93	2.92	2.03	1.81
619	5.99	5.71	5.17	4.73	4.36	4.06	3.00	2.29	1.94
643	6.41	6.00	5.71	5.02	4.63	4.43	3.36	2.68	2.44
697		7.20	6.68	6.24	5.84	5.39	4.26	3.56	3.28

of comparison and analysis other curves have been plotted. These are shown in Figs. 9–34. The curves given in Figs. 9–16, show the effect of intensity of light on the shape of the visibility curves; in Figs. 17–26, the effect of state of adaption of the eye; and in Figs. 27–34, the effect of size of photometric field. In this group of curves the following scheme has been used to indicate the various factors:

(1) In all the curves for light adaptation the exeperimentally determined points have been plotted as crosses; in those for dark adaptation the points have been plotted as circles.

TABLE XII

Showing in logarithmic terms the amounts of energy per second of spectrum lights required to match each of the photometric standards under dark adaptation; size of field 4° 49′. In deriving these values 1×10^{-14} watt is taken as a unit.

Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	0.2 m.c.	0.02 m.c.	0.01 m.c.	0.002 m.c.	0.001 m.c.
454 mμ				5.87	5.56	5.08	4.04	2.55	2.08	1.32	0.95
470				5.64	5.36	4.84	3.83	2.29	1.87	1.08	0.71
485			5.93	5.53	5.19	4.77	3.63	2.26	1.81	0.95	0.64
502.5	5.90	5.77	5.40	4.98	4.75	4.31	3.20	2.15	1.76	0.85	0.51
522.5	5.60	5.48	5.14	4.74	4.39	3.99	3.01	1.97	1.59	0.81	0.59
540	5.48	5.32	4.90	4.54	4.19	3.81	2.83	1.77	1.44	0.74	0.65
557	5.43	5.22	4.88	4.48	4.16	3.79	2.86	1.86	1.69	0.98	0.79
580	5.43	5.22	4.90	4.48	4.19	3.81	2.94	2.11	2.00	1.35	1.09
597.5	5.71	5.39	5.12	4.54	4.53	3.96	3.08	2.24	2.17	1.55	1.39
619	6.04	5.74	5.32	5.01	4.58	4.21	3.19	2.52	2.50	2.03	1.75
643	6.38	6.02	5.87	5.48	5.09	4.63	3.64	2.92	2.83	2.48	2.39
697		7.22	6.92	6.55	6.19	5.52	4.57	3.93	3.82	3.52	3.44

(2) The size of field and level of intensity employed are indicated by the type of line joining the plotted points as shown in the following scheme.

High Intensity, Extrafoveal Size of Field, ————————————
High Intensity, Foveal Size of Field, —— . . —— . . —— . . —— . .
Medium Intensity, Extrafoveal Size of Field, — — . — — . — — . — — .
Medium Intensity. Foveal Size of Field, ...
Low Intensity Extrafoveal, —— —— —— —— —— —— ——
Low Intensity Foveal, —— . —— . —— . —— . —— . —— . —— .

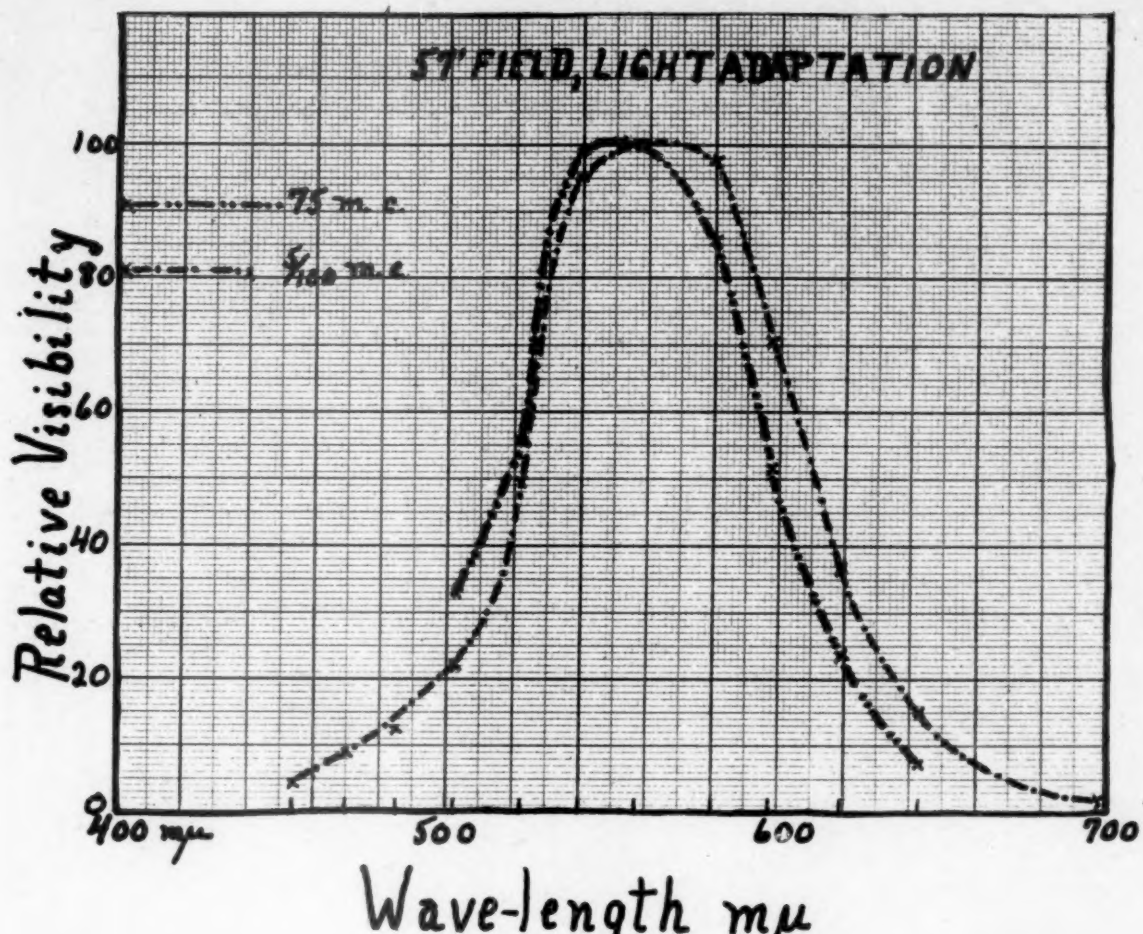
A. The Effect of Intensity of Light on the Relation Sensitivity to the Different Wave-lengths

The assembled curves in Fig. 8 provide an opportunity for studying the effect of changes of intensity on relative visibility under four conditions: dark adaptation with extrafoveal size of field; dark adaptation with foveal size of field; light adaptation with extrafoveal size of field; and light adaptation with foveal size of field. The most marked effect occurs under the first of these conditions and the least marked under the fourth. The effect for dark adaptation is in general greater than for light and for an extrafoveal size of field than for a foveal size. The effect of change of intensity is further shown in Figs. 9–12. In these figures the curves for the highest and lowest intensities used under each of the four conditions noted above are given. These curves

Table XIII

Showing the relative visibilities of spectrum lights under light adaptation; size of field 57 min. In this and the three following tables visibility is taken as the reciprocal of the energy of light required to match the photometric standard at the various intensities. For convenience of comparison these reciprocals have been reduced to a scale in which 100 has been chosen to represent the maximum value.

Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	1 m.c.	0.2 m.c.	0.1 m.c.	0.05 m.c,
454 mμ					4.11	3.69	4.91	4.22	3.17	4.14
470				6.3	8.15	7.99	10.8	8.99	7.22	9.92
485			7.63	7.19	7.92	8.38	8.56	9.84	9.68	12.2
502.5	33.0	25.3	27.3	29.7	31.5	31.1	26.7	20.6	18.9	22.0
522.5	55.6	51.4	50.0	60.0	58.9	62.3	66.6	41.6	41.1	49.4
540	99.0	85.6	83.6	94.1	96.7	90.9	93.0	92.4	94.3	95.0
557	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
580	85.4	82.3	82.9	92.6	84.0	90.2	96.3	82.2	86.2	97.8
597.5	51.8	48.6	48.4	53.3	58.1	71.0	71.7	61.6	69.5	70.7
619	23.9	20.7	20.5	22.4	37.6	38.6	37.0	38.3	38.8	36.9
643	7.21	6.85	6.04	7.32	14.5	16.9	17.9	15.7	15.9	15.0
697		0.398	0.443	0.442	0.854	1.45	1.6	0.947	1.85	1.73



FIGS. 9–12. Showing for comparison visibility curves for the highest and lowest intensities used under each of the following conditions: light adaptation, foveal size of field; dark adaptation, foveal size of field; light adaptation, extrafoveal size of field; dark adaptation, extrafoveal size of field.

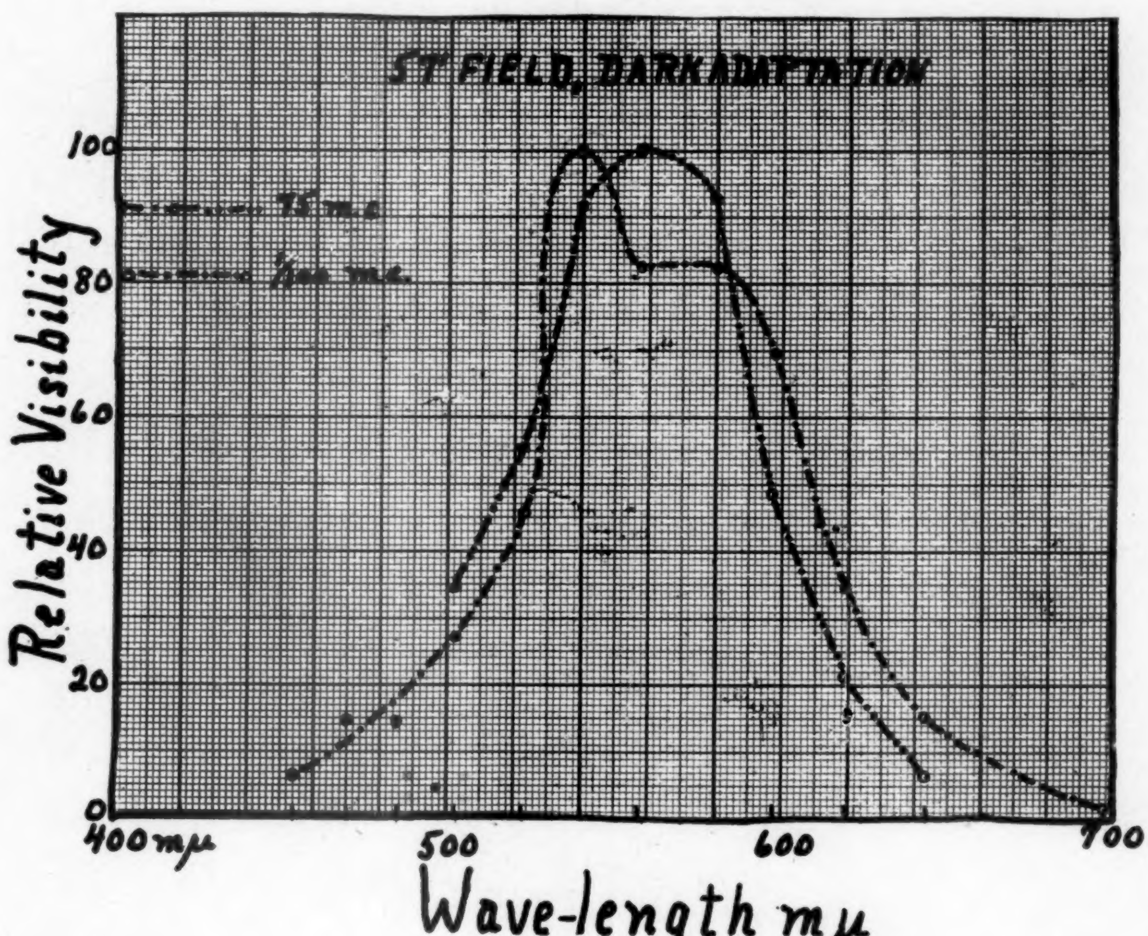


FIG. 10

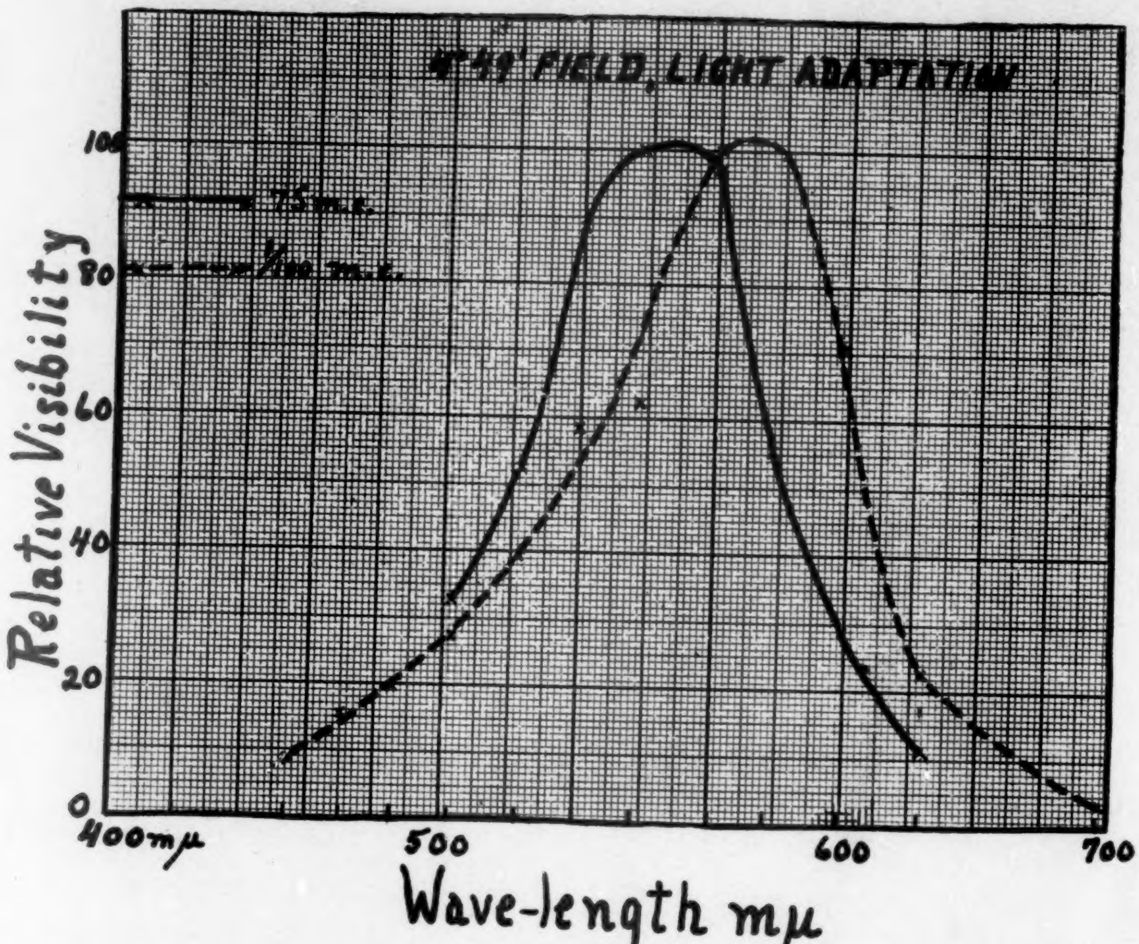

4°49' FIELD, LIGHT ADAPTATION
Relative Visibility
Wave-length mμ
400mμ
500
600
700
0
20
40
60
80
100
75 m.c.

Fig. 11

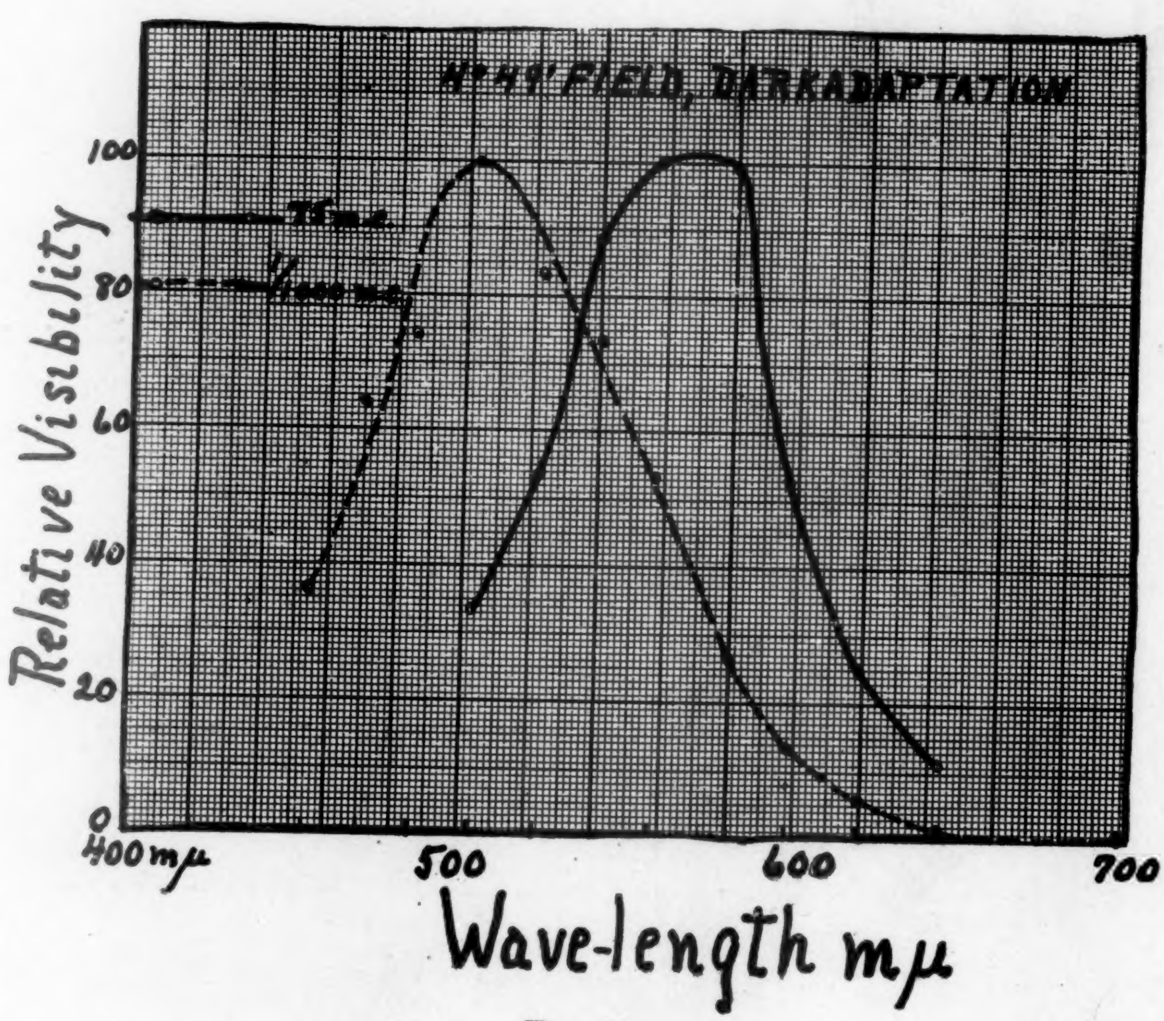

4°49' FIELD, DARK ADAPTATION
Relative Visibility
Wave-length mμ
400mμ
500
600
700
0
20
40
60
80
100
75 m.c.

Fig. 12

TABLE XIV

Showing the relative visibilities of spectrum lights under dark adaptation; size of field 57 min.

Wave-length	75 m.c	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	1 m.c.	0.2 m.c.	0.1 m.c.	0.05 m.c.	0.02 m.c.	0.01 m.c.
454 mμ					4.52	3.51	4.26	5.21	3.55	3.64	5.86	6.38
470				5.77	7.66	8.88	7.03	10.1	7.08	7.99	9.29	14.7
485			9.13	6.63	7.99	8.66	9.85	10.9	7.81	9.39	11.4	14.4
502.5	34.4	29.5	31.5	28.4	29.5	33.8	22.0	23.5	19.3	21.5	22.3	27.0
522.5	55.25	59.4	68.3	59.2	65.8	69.7	51.6	42.1	45.9	43.1	39.2	45.4
540	91.7	88.5	98.7	80.6	97.4	94.1	85.9	98.9	100.0	100.0	100.0	100.0
557	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.5	94.2	85.5	82.7
580	92.7	83.1	89.4	90.3	86.7	89.4	95.9	91.9	91.6	85.4	81.8	82.1
597.5	48.7	43.9	57.6	45.1	59.9	65.1	75.7	61.7	72.3	59.6	59.7	69.4
619	21.3	19.6	20.4	19.2	34.0	29.6	39.0	35.8	37.6	36.8	35.0	34.85
643	6.45	7.19	7.68	5.87	14.0	9.75	17.5	15.5	15.4	14.6	14.7	15.1
697		0.369	0.612	0.432	0.926	0.869	1.28	1.31	1.77	1.56	1.49	1.55

TABLE XV

Showing the relative visibilities of spectrum lights under light adaptation; size of field 4 deg. 49 min.

Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	0.2 m.c.	0.02 m.c.	0.01 m.c.
454 mμ				3.7	3.93	4.19	4.89	12.7	8.82
470				6.68	6.39	8.82	8.72	20.0	15.5
485			7.25	7.9	8.56	10.3	10.0	20.9	19.8
502.5	32.9	28.8	23.85	27.7	25.8	31.5	18.8	26.3	27.6
522.5	52.3	52.4	45.9	59.7	51.8	56.2	35.6	40.9	39.4
540	88.3	88.4	76.9	91.9	83.5	94.6	76.1	62.8	58.6
557	100.0	100.0	100.0	100.0	100.0	100.0	86.4	71.6	62.2
580	97.1	98.8	95.7	93.4	99.6	96.1	100.0	100.0	100.0
597.5	55.4	59.5	56.6	83.1	73.2	69.3	67.3	95.7	99.3
619	28.8	29.7	41.1	50.6	61.5	52.4	56.2	66.3	70.9
643	11.0	15.1	11.9	26.45	32.7	22.2	24.1	27.3	22.8
697		0.96	1.25	1.59	2.06	2.41	3.01	3.57	3.27

are intended to bring out more clearly the range of change produced by the given change of intensity.

Dark adaptation, extrafoveal size of field. Under these conditions it will be seen that the point of maximum sensitivity shifts towards the short wave-lengths with decrease of intensity. Thus at 75 m.c the point of maximum sensitivity is at 557 mμ and at 0.001 m.c. it is at 502.5 mμ. Between 75 m.c. and 2 m.c. changes in the shape of the curve occur but there is little change in the position of the maximum. Thus the greater part of the shift of the maximum occurs at intensities below 2 m.c. as well as the more pronounced changes in the shape of the curve. Between 2 and 0.001 m.c. the changes in the shape of the curve are seen to be

TABLE XVI

Showing the relative visibilities of spectrum lights under dark adaptation; size of field 4 deg. 49 min.

Wave-length	75 m.c.	40 m.c.	20 m.c.	10 m.c.	5 m.c.	2 m.c.	0.2 m.c.	0.02 m.c.	0.01 m.c.	0.002 m.c.	0.001 m.c.
454 mμ				4.03	3.97	5.03	6.35	16.7	22.6	25.9	36.4
470				6.86	6.31	8.81	10.1	30.2	36.5	45.2	64.1
485			8.88	8.79	9.24	10.4	16.1	32.3	42.7	61.9	74.2
502.5	33.7	28.0	30.1	31.1	25.7	30.1	43.6	41.3	47.8	77.0	100.0
522.5	53.4	54.9	55.3	54.4	58.4	62.3	67.0	63.4	69.5	84.2	83.2
540	88.7	79.1	97.0	86.3	92.5	95.5	100.0	100.0	100.0	100.0	73.5
557	100.0	100.0	100.0	100.0	100.0	100.0	94.6	81.4	55.2	58.2	53.15
580	99.6	99.1	96.8	98.3	93.2	93.5	80.1	46.2	27.4	25.0	26.2
597.5	52.7	66.8	57.4	85.9	67.0	66.9	57.9	33.9	18.3	15.6	13.4
619	24.4	29.6	36.9	29.2	37.9	37.7	44.7	17.8	8.52	5.18	5.81
643	11.7	15.5	10.4	9.81	11.9	14.4	16.0	7.0	4.08	1.84	1.33
697		0.992	0.923	0.852	0.925	1.85	1.84	0.693	0.417	0.169	0.118

quite irregular. These irregularities seem to indicate that the relative increase in sensitivity to the short wave-lengths which results ultimately in the shift of the point of maximum sensitivity from 557 mμ to 502.5 mμ, occurs sooner for some wave-lengths than for others. That is, the irregularities in the shape of the curve represent stages in the shift of the position of the curve. Prior to the beginning of the shift and at its close, 0.001 m.c., the curves show a regularity of outline, being in fact somewhat similar to a slightly skewed probability curve. The curve for 0.001 m.c., the lowest intensity investigated, was given, it will be remembered, in the historical section, Fig. 1, p. 14, for comparison with the results of earlier investigations made at low intensities and with extrafoveal sizes of field. It is roughly similar to the greater number of these but resembles most closely the curve determined by Hecht. Hetcht's work, as was noted in that section, is perhaps the most reliable of the previous investigations made at low intensities.

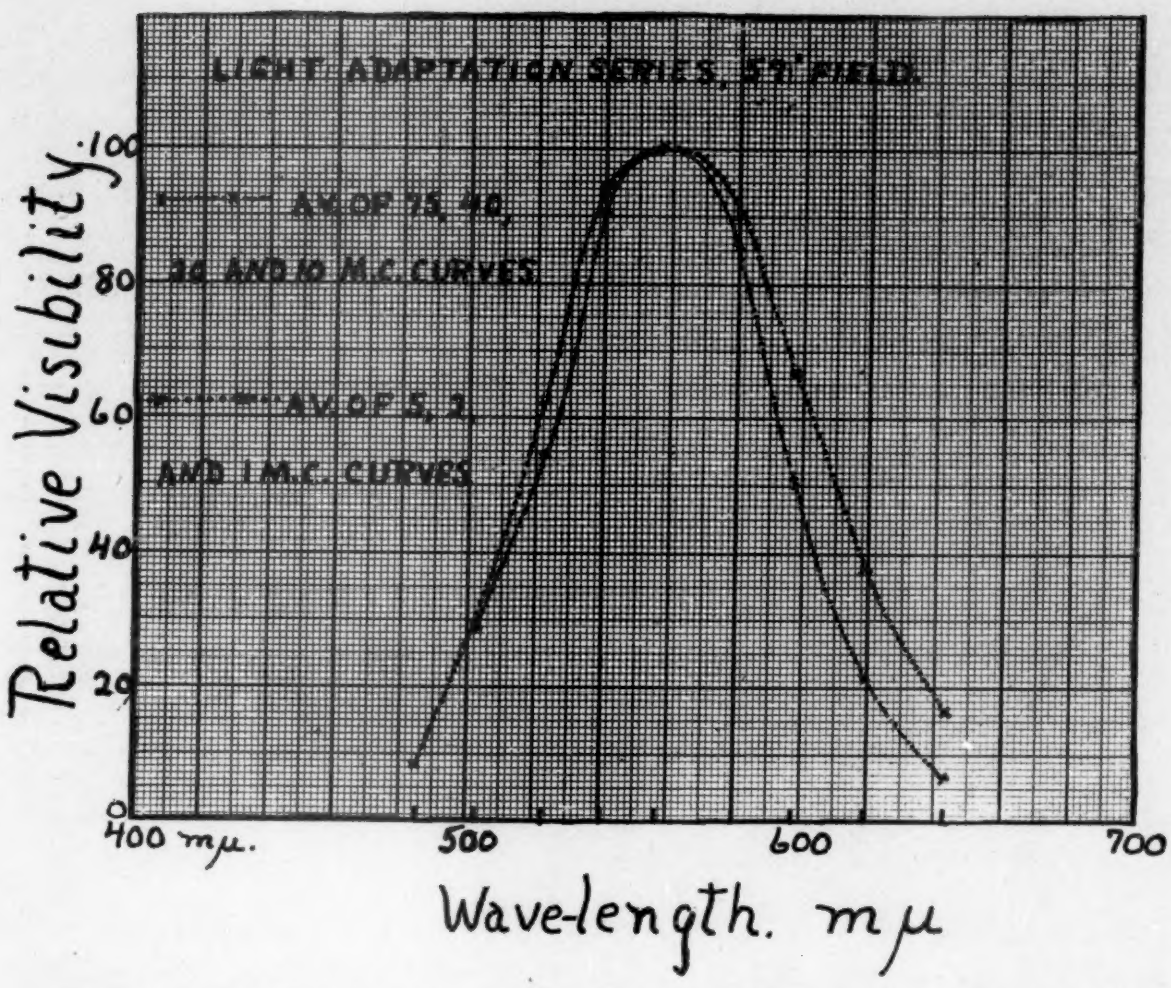
Dark adaptation, foveal size of field. When a foveal size of field was used with dark adaptation the point of maximum sensitivity was again found to shift toward the short wave-lengths with decrease of intensity; but the changes in the curve in this case are less marked and probably begin at a lower intensity. At the higher intensities, as before, the point of maximum sensitivity was at 557 mμ. At 0.2 m.c. a slight tendency to shift toward the shorter wave-lengths may be noted, and at 0.02 and 0.01 m.c. the maximum is found to be around 540 mμ. Again the shift is accompanied by an irregular change in the shape of the curve. Irregularity of change in the shape of the curve seems in general to characterize any considerable shift in the position of a visibility curve. That is, the eye apparently is not only highly selective in its response to wave-length but this selectiveness changes irregularly with the change of intensity, particularly at the lower levels of intensity under the condition of dark adaptation. This fact has not come out so clearly in former studies because of the smaller number of intensities used.

Light adaptation, extrafoveal size of field. When an extra-

foveal size of field was used with light adaptation a shift in the position of the curve was found to accompany a decrease of intensity, but the direction of the shift under these conditions is the reverse of that obtained with dark adapation. Between the intensities of 2 and 0.01 m.c. the point of maximum sensitivity moved from 557 to 580 mμ and the shape of the curve changed slightly. The above changes in shape and position, however, do not result in as much irregularity in the shape of the curve as was found with dark adaptation. As has already been noted, under light adaptation, the eye shows in general a greater regularity of response than under dark adaptation.

Light adaptation, foveal size of field. With a foveal size of field and light adaptation, no shift in the point of maximum sensitivity is found to occur within the range of intensities employed and for the wave-lengths investigated. It remains at 557 mμ down to 0.05 m.c., the lowest intensity at which it was feasible to make the determinations for this state of adaptation and size of field. As before, however, changes in the shape of the curve are found to accompany a decrease of intensity. While smaller than those obtained under any of the other conditions employed, they are by no means negligible. For example, the ordinates of the curves for 1 and 0.2 m.c. differ by more than 10 per cent at nine of the twelve points, at which determinations were made. At two of these points, 522.5 mμ and 687 mμ the differences were as much as 33 and 41 per cent respectively.

While the preceding analysis shows that for all four of the conditions investigated the most striking changes in the shape of the curve do not occur until a low intensity, approximately 0.2 m.c., is reached, a careful examination of the data for the higher intensities reveals that here also significant changes in relative sensitivity accompany changes of intensity if sufficiently large ranges of change are considered. These effects are somewhat obscured, in the individual curves shown in Fig. 8, because of the low precision of the judgment in heterochromatic photometry and the magnitude of the changes of intensity represented. In the curves given in Figs. 13–16, therefore, the data have been



FIGS. 13–16. Showing for comparison visibility curves for high and medium intensities under each of the following conditions: light adaptation, foveal size of field; dark adaptation, foveal size of field; light adaptation, extrafoveal size of field; and dark adaptation, extrafoveal size of field.

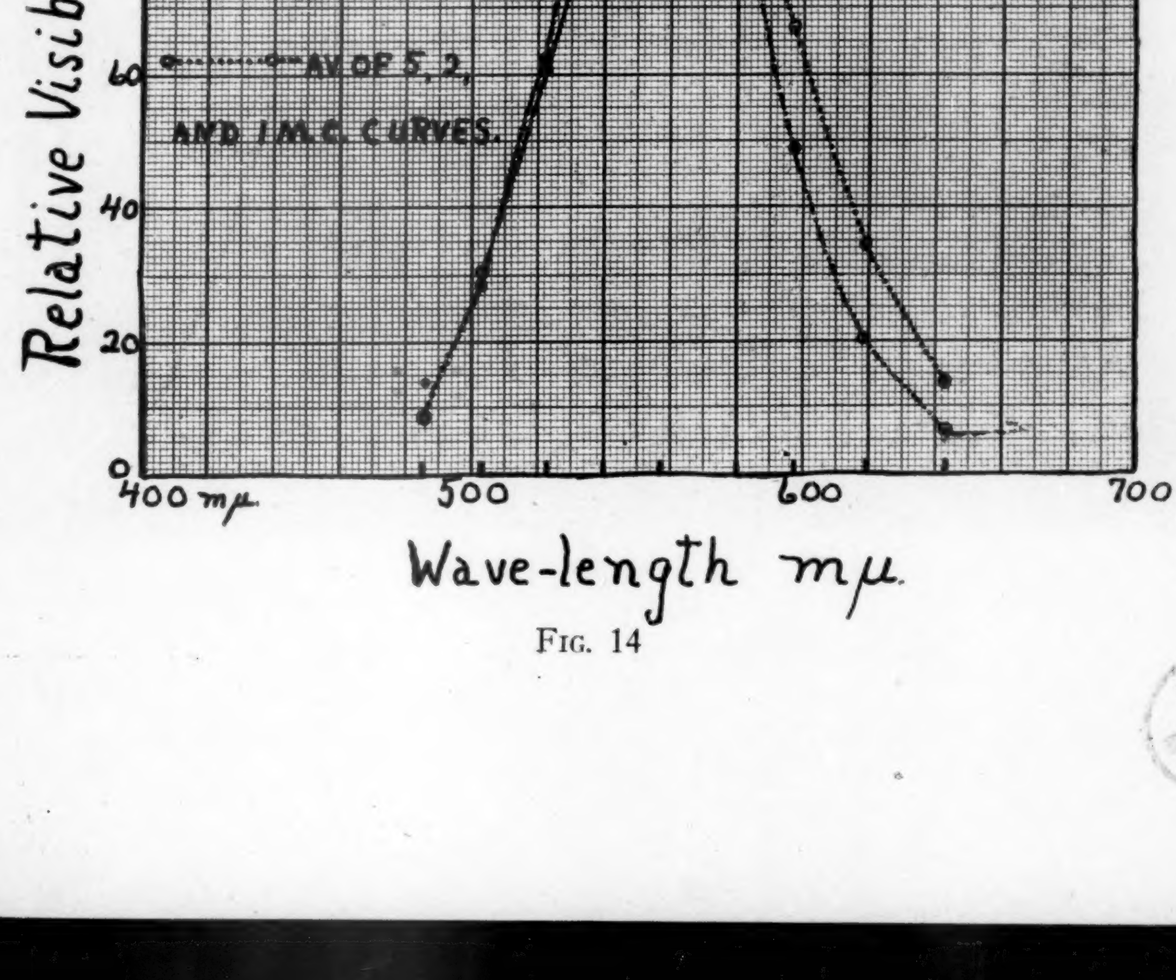


FIG. 14

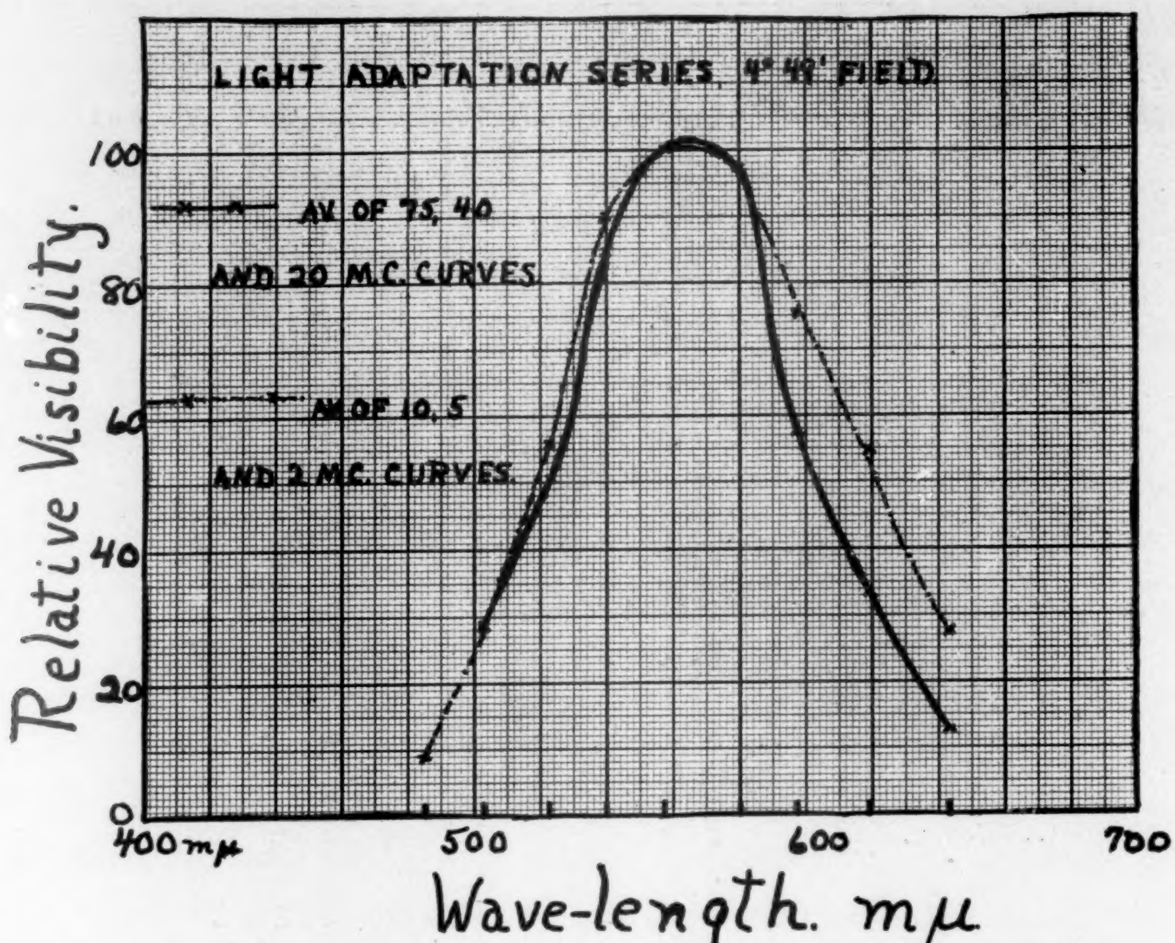

LIGHT ADAPTATION SERIES. 4° 49' FIELD
AV OF 75, 40
AND 20 M.C. CURVES
AV. OF 10, 5
AND 2 M.C. CURVES.
Relative Visibility.
100
80
60
40
20
0
400 mμ
500
600
700
Wave-length. mμ

FIG. 15

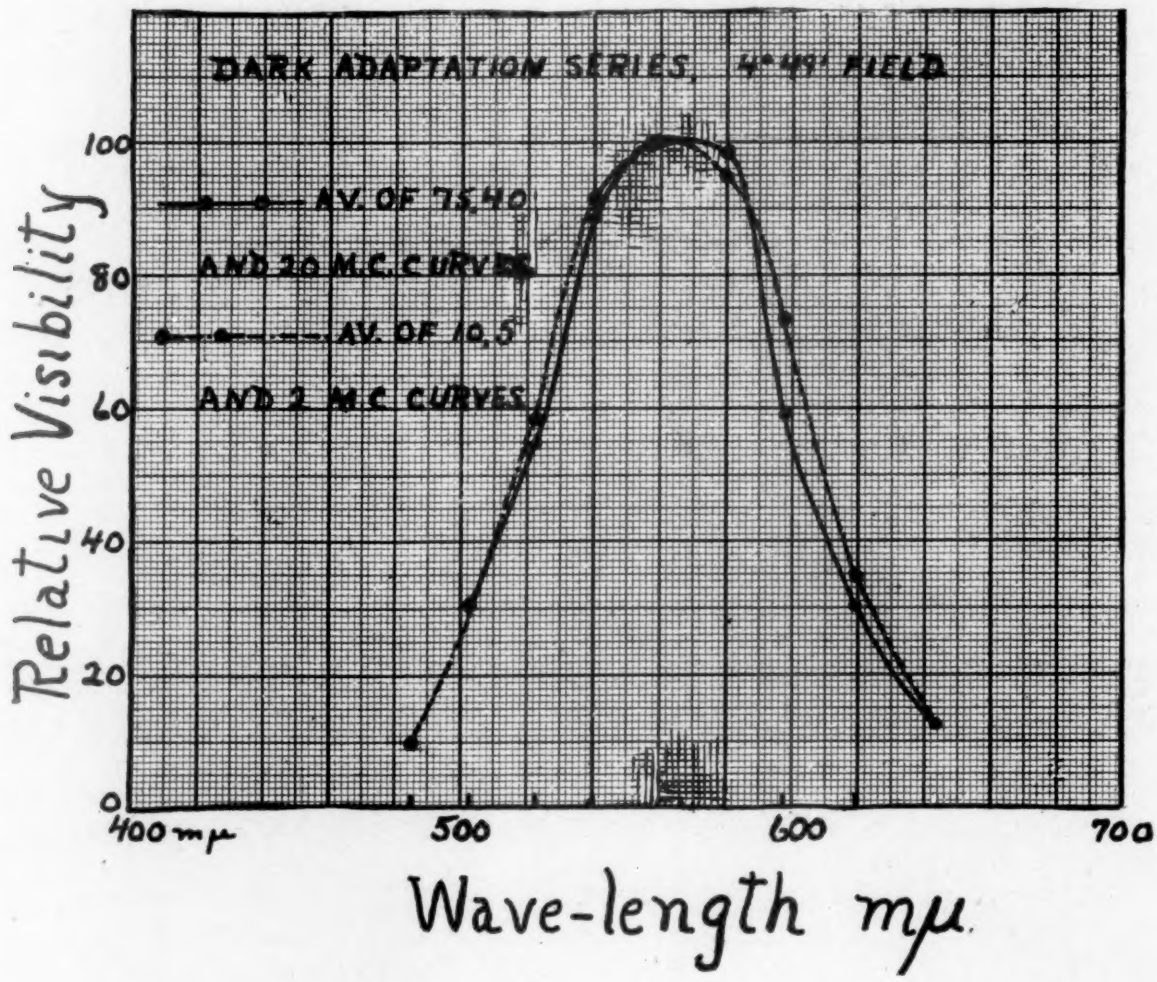

DARK ADAPTATION SERIES. 4° 49' FIELD
AV. OF 75, 40
AND 20 M.C. CURVES
AV. OF 10, 5
AND 2 M.C. CURVES
Relative Visibility
100
80
60
40
20
0
400 mμ
500
600
700
Wave-length mμ.

FIG. 16

replotted to show a comparison of the average of the results obtained at high and at medium intensities [1] for each of the lights employed. The data from which these curves were plotted are given in Table XVII. An examination of these average curves shows that in passing from high to medium intensity there is an

TABLE XVII

Showing a comparison of the average relative visibilities for a group of high and a group of medium intensities of light. The values given represent the average ordinates of the visibility curves of each group.

	Light Adaptation Size of Field 57 min.		Dark Adaptation Size of Field 57 min.		Light Adaptation Size of Field 4 deg. 49 min.		Dark Adaptation Size of Field 4 deg. 49 min.	
Wave-length	High Intensities	Medium Intensities	High Intensities	Medium Intensities	High Intensities	Medium Intensities	High Intensities	Medium Intensities
454 mμ		4.24		4.1				
470		8.98		7.84				
485		8.29		8.83		8.92		9.48
502.5	28.8	29.8	30.9	28.4	28.5	28.3	30.6	29.0
522.5	54.2	62.6	60.5	62.4	50.2	55.9	54.5	58.4
540	90.6	93.5	89.8	92.5	84.5	90.0	88.3	91.4
557	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
580	85.8	90.2	88.85	90.7	97.2	96.4	98.5	95.0
597.5	50.5	66.9	48.8	66.9	57.2	75.2	59.0	73.3
619	21.9	37.7	20.1	34.2	33.2	54.8	30.3	34.9
643	6.85	16.4	6.29	13.75	12.7	27.1	12.5	12.1
697		1.3		1.03				

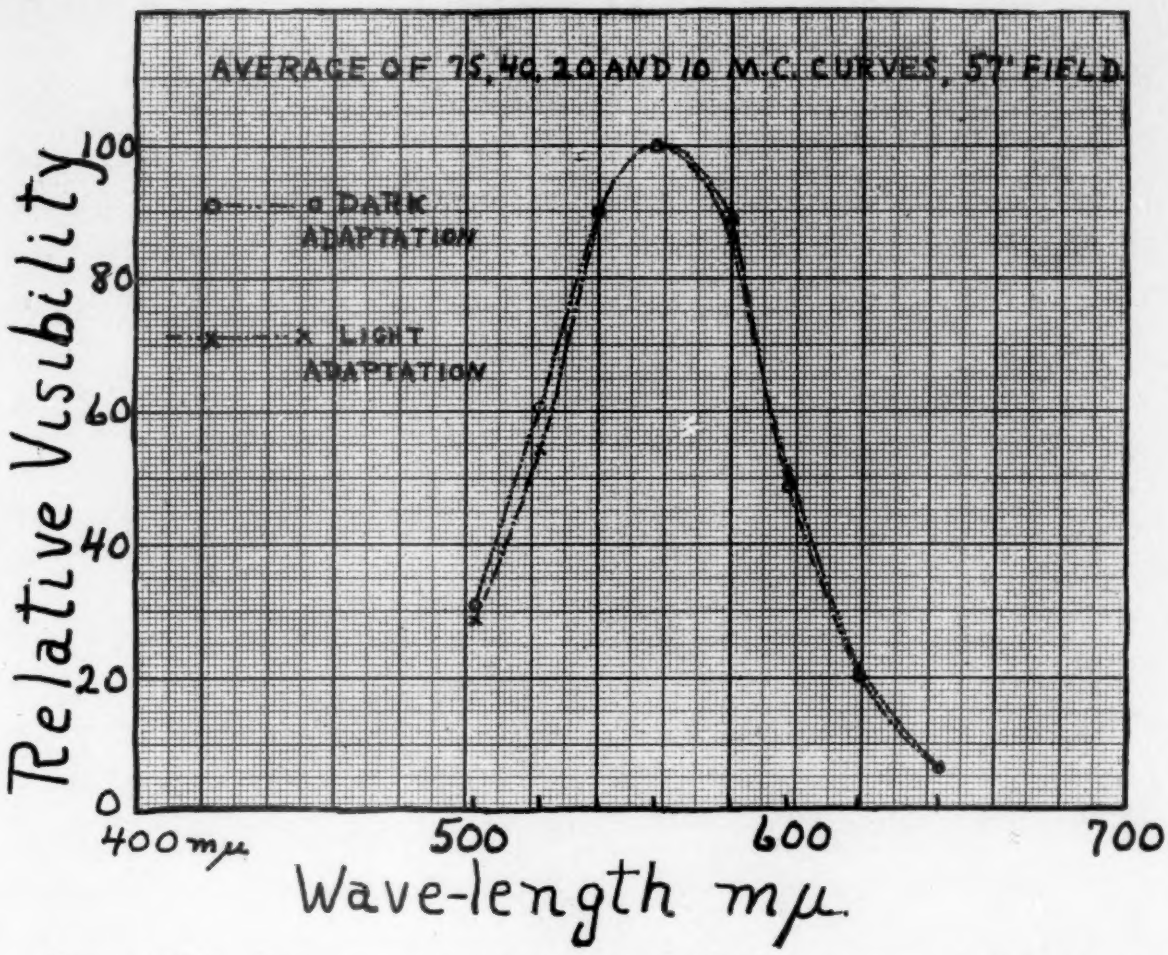
increase of sensitivity in the orange and red parts of the spectrum and in the region between blue and green for all of the conditions tested, foveal and extrafoveal sizes of field, and light and dark adaptation. The increase of sensitivity to red and orange, however, is considerably greater than to blue-green. Also it is less pronounced for the foveal size of field under dark adaptation than for other conditions employed.

In this connection it is significant to note that definite changes in the shape of the curve are found to occur within the range of intensities ordinarily used in photometry. Under three of the four experimental conditions employed the magnitude of these

[1] In the foveal series the 10 m.c. curve is included with the high intensity group. In the extrafoveal series, however, an examination of the separate curves showed that this curve was more similar to the group of medium intensity curves. In the foveal series, therefore, the curves for 75, 40, 20, and 10 m.c. are combined to give the average high intensity curve; in the extrafoveal series, those for 75, 40 and 20 m.c. only are included in the average high intensity curve.

changes in the red ranges from approximately 30 per cent increase of sensitivity at 597 mμ to more than 100 per cent at 643 mμ. The changes are much less in amount in the case of wave-lengths below 557 mμ and are less under dark adaptation with extra-foveal size of field, where the maximum increase in sensitivity at 597.5 mμ is about 24 per cent. Since, however, the ordinary photometric standards radiate a large proportion of their energies in the orange and the red these differences are not negligible, and we should expect from these results that the photometric ratings of these lights would vary by significant amounts if the determinations are made at different levels of intensity at the photometer head.

A comparison with the results of previous investigators may also be of interest at this point. Such a comparison is rendered difficult because of the difference in the problems studied and the difference in the experimental conditions employed. When their work is considered collectively, however, a few points of contact with our own may be found. In these cases as much agreement is found, perhaps, as could be expected. For example (1) it has been claimed both by Abney and Festing and by Dow that the Purkinje effect does not begin until an intensity of about 0.2 m.c. is reached. The curves presented in Fig. 8, show that a shift in the position of the curve occurs at approximately this intensity. (2) While our curves do not show a shift of position until a low intensity is reached, changes of shape are seen to occur in varying amounts at all of the intensities investigated. This result is confirmed by Koenig, by Ferree and Rand, and by Ives, all of whom agree in finding selectiveness of response to intensity still present at the highest intensities investigated by them. The failure of Abney and Festing and of Dow to find these changes in relative sensitivity at the higher intensities was probably due to the limited range of intensities investigated. (3) The curves in Fig. 8 are seen to become broader with decrease of intensity or conversely to become narrower with increase of intensity. This is in general agreement with the results obtained by Ives and by Ferree and Rand, and in disagreement with the results obtained by Koenig.



Figs. 17–20. Showing for comparison visibility curves for light and dark adaptation under each of the following conditions: high intensity, foveal size of field; high intensity, extrafoveal size of field; medium intensity, foveal size of field; medium intensity, extrafoveal size of field.

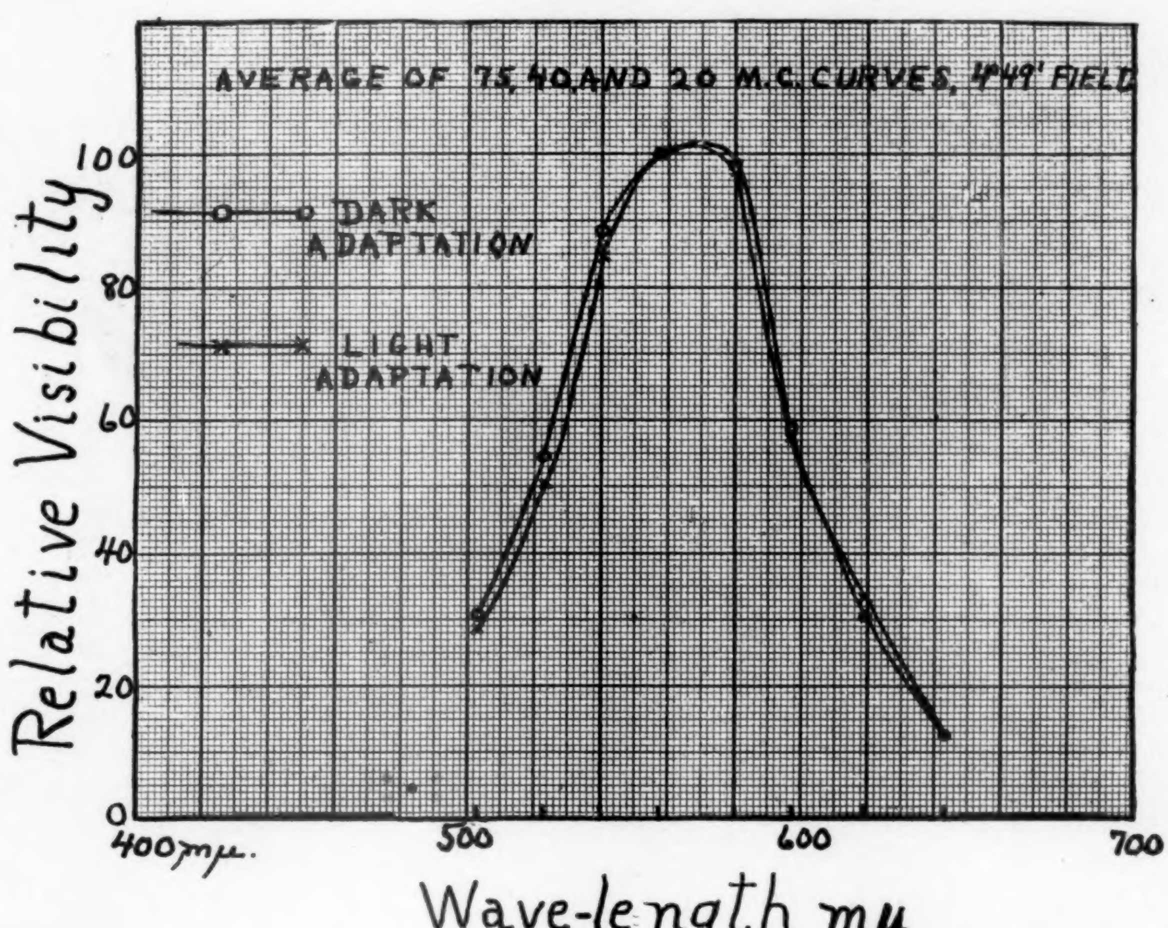
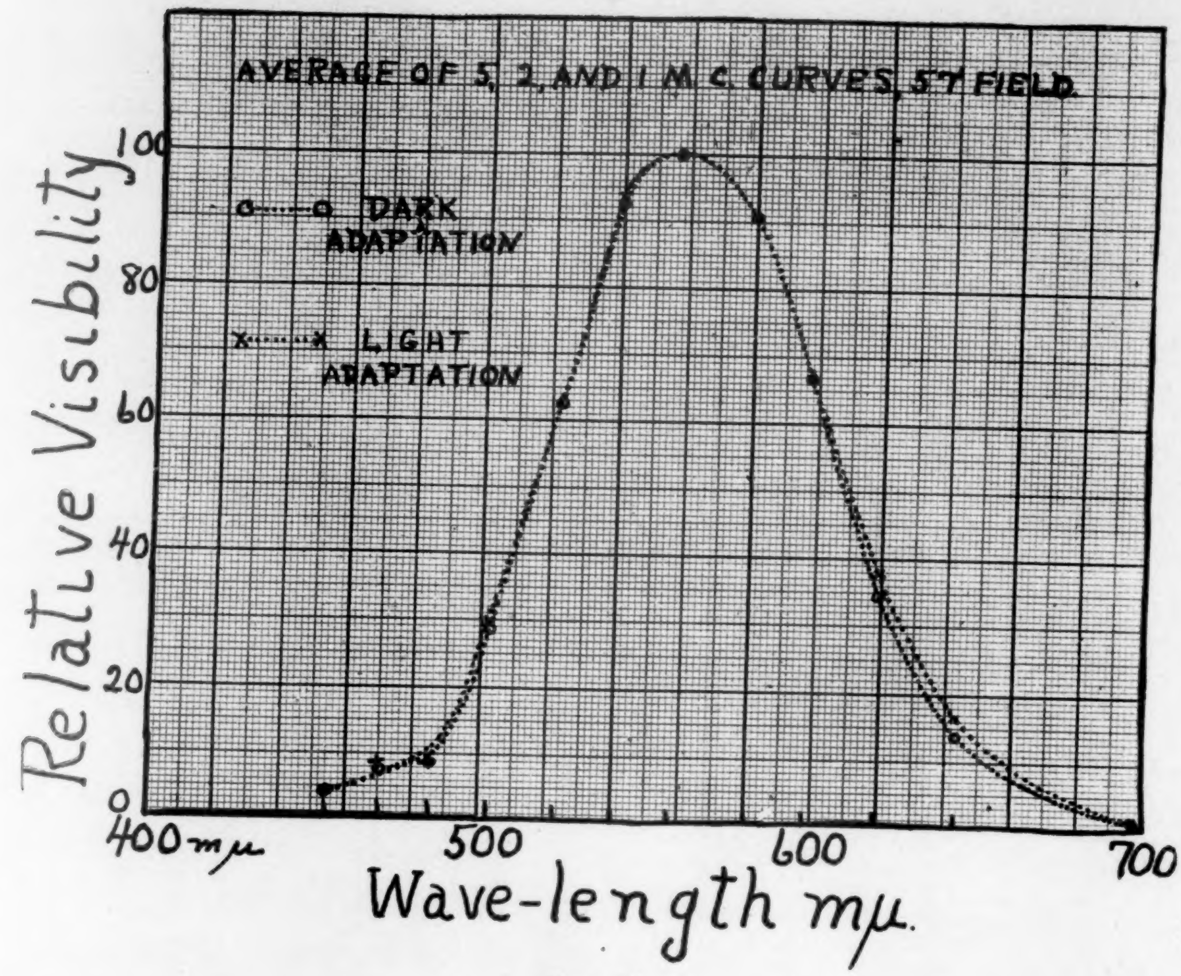
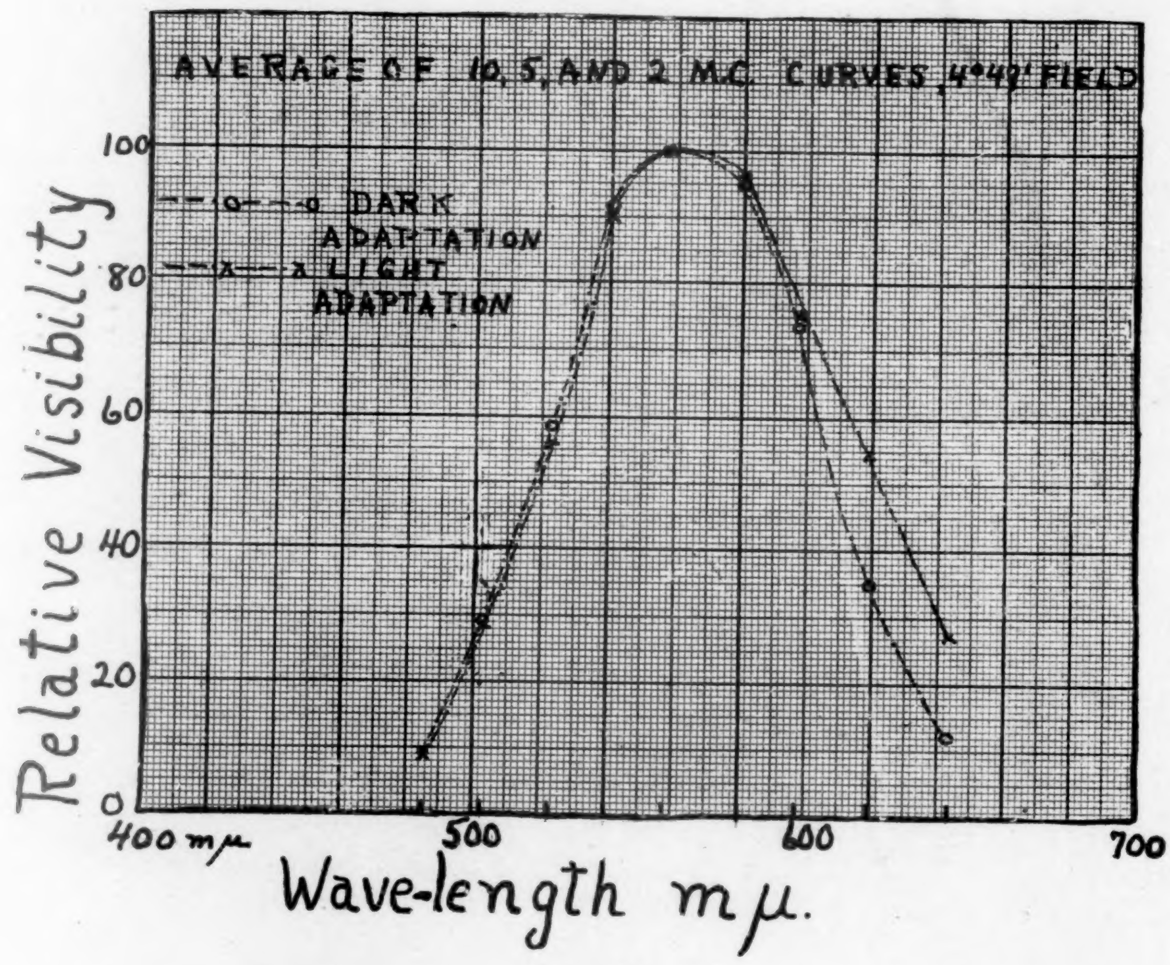


Fig. 18



AVERAGE OF 5, 2, AND 1 M.C. CURVES, 5°7' FIELD.
o-----o DARK ADAPTATION
x-----x LIGHT ADAPTATION
Relative Visibility
0
20
40
60
80
100
400 mμ
500
600
700
Wave-length mμ.

FIG. 19



AVERAGE OF 10, 5, AND 2 M.C. CURVES, 4°42' FIELD
--o--o DARK ADAPTATION
--x--x LIGHT ADAPTATION
Relative Visibility
0
20
40
60
80
100
400 mμ
500
600
700
Wave-length mμ.

FIG. 20

The data given by Ives for the two sizes of field most comparable with our own, namely, 4.38 and 1.86 deg., show that between 270 and 8.9 illumination units, decrease of intensity is accompanied by an increase in relative luminosity in the green and also in the red and orange. These changes result in a broadening of the luminosity curves. It seems fair to infer that if the results had been presented in the form of visibility rather than luminosity curves, they too would have been found to broaden with decrease of intensity. The data of Ferree and Rand when plotted in the form of visibility curves (see Fig. 3) show agreement with our own on this and another point. For (a) the curves increase in breadth from 75 to 12.5 m.c., the range of intensities investigated; and (b) the increase in sensitivity is more marked on the red side of the curve than on the blue side. Curves plotted from the data of Koenig as recalculated by Nutting, however, become narrower instead of broader with decrease of intensity. In this connection it should be noted that the determinations by Ferree and Rand were made under conditions much more nearly comparable with our own than those by Koenig. Koenig's procedure, as has been noted in the historical section, contained a number of possible sources of error, namely, the variation of intensity by means of the collimator slit, the use of a green photometric standard, various ambiguities in the specification of the levels of intensity used, uncertainties in the determination of the energy values needed for a quantitive comparison of sensitiveness, etc.

B. The Effect of State Adaptation of the Eye on the Visibility Curve

In Figs. 17–20 curves for light and dark adaptation for the same range of intensities [1] and the same size of field have been plotted in one chart. This has been done in order to show the effect of a change in the observer's state of adaptation when the size of field and the intensity of light are held constant.

High intensity, foveal and extrafoveal sizes of field. At the higher intensities, it will be noted, there are only slight differences

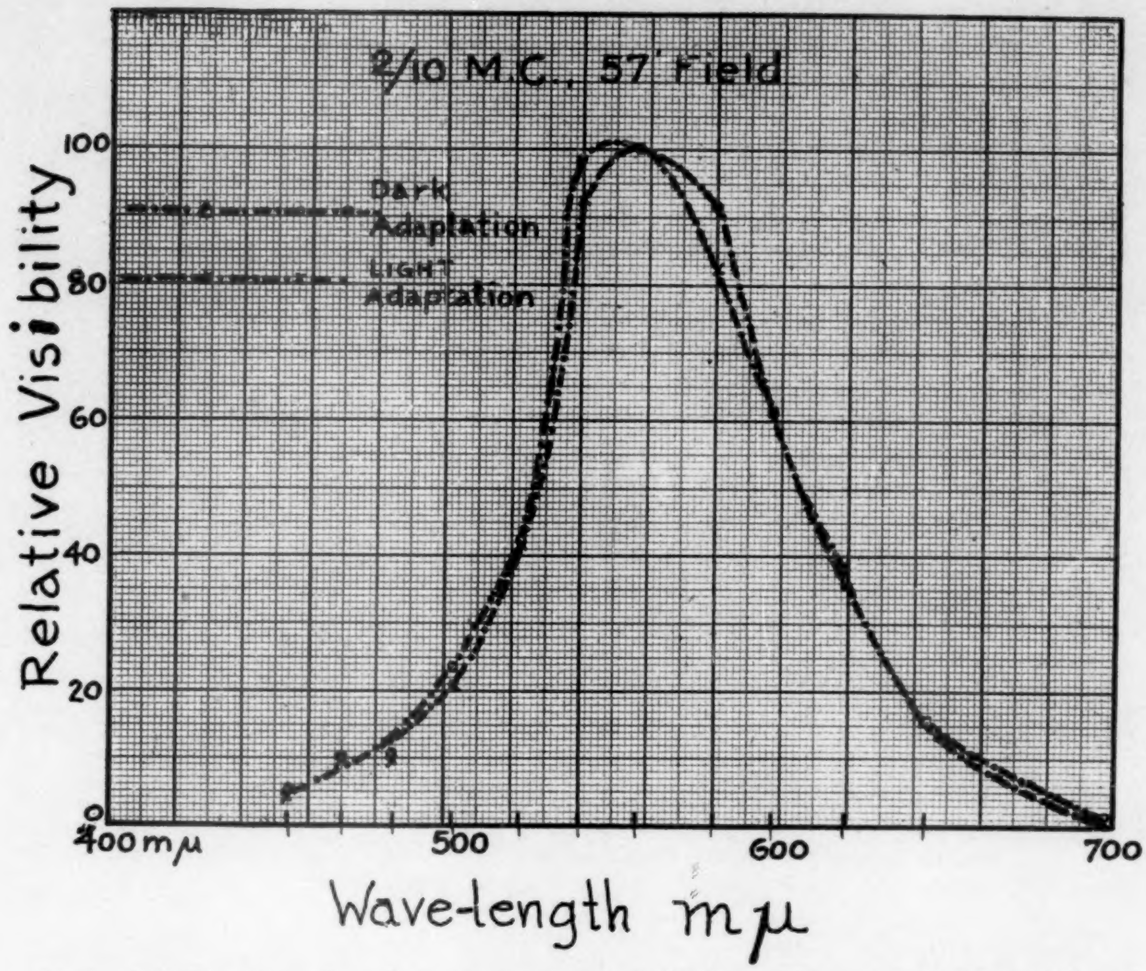
[1] The data used in this comparison are taken from Table XVIII, in which the average visibilities for certain ranges of intensity are given.

in the curves for light and dark adaptation. The former are somewhat lower on the blue side than the corresponding curves for dark adaptation. This is true for both the foveal and extra-foveal sizes of field. These curves are shown in Figs. 17 and 18.

Medium intensity, foveal and extrafoveal sizes of field. At medium intensities with foveal sizes of field (Fig. 19), the curves for light and dark adaptation show no differences which are large enough to be considered significant. In the case of the larger size of field (Fig. 20), however, the curve for light adaptation is much higher in the red than the corresponding curve for dark adaptation. For example, the ordinates of the curve for dark adaptation at wave-lengths 619 and 643 mμ are 34.9 and 12.1 respectively, whereas the corresponding ordinates of the curve for light adaptation are 54.8 and 27.1. This is equivalent to an increase in relative sensitivity with light adaptation of approximately 57 per cent at 619 mμ and 124 per cent at 643 mμ.

Low intensity, foveal and extrafoveal sizes of field. The effect of adaptation at very low intensities is very striking, as is shown in Figs. 21–26. The differences are greatest for the extrafoveal size of field. For this size of field the point of maximum sensitivity shifts towards the short wave-length end of the spectrum under the condition of dark adaptation, while with light adaptation a shift in the opposite direction occurs. In the foveal series the chief differences between the curves for light and dark adaptation are in the region near the point of maximum sensitivity. Thus at 0.05 m.c., the lowest intensity at which observations were made for both light and dark adaptation, the ordinates of the curves for dark adaptation are smaller between wave-lengths 560 and 600 mμ and larger at 540 mμ than those of the corresponding curves for light adaptation. The latter approximate the shape of the normal visibility curve while the former are irregular in shape and skewed toward the blue wave-lengths.

In order to show further the effect of state of adaptation two brief additional studies were conducted. (a) A few determinations were made with the observer's eye adapted to a lower level of illumination. For example, a curve for 10 m.c. was determined



FIGS. 21–26. Showing for comparison visibility curves for light and dark adaptation under each of the following conditions of low intensity: 0.2 m.c., foveal size of field; 0.1 m.c., foveal size of field; 0.05 m.c., foveal size of field; 0.2 m.c., extrafoveal size of field; 0.02 m.c., extrafoveal size of field; 0.01 m.c., extrafoveal size of field.

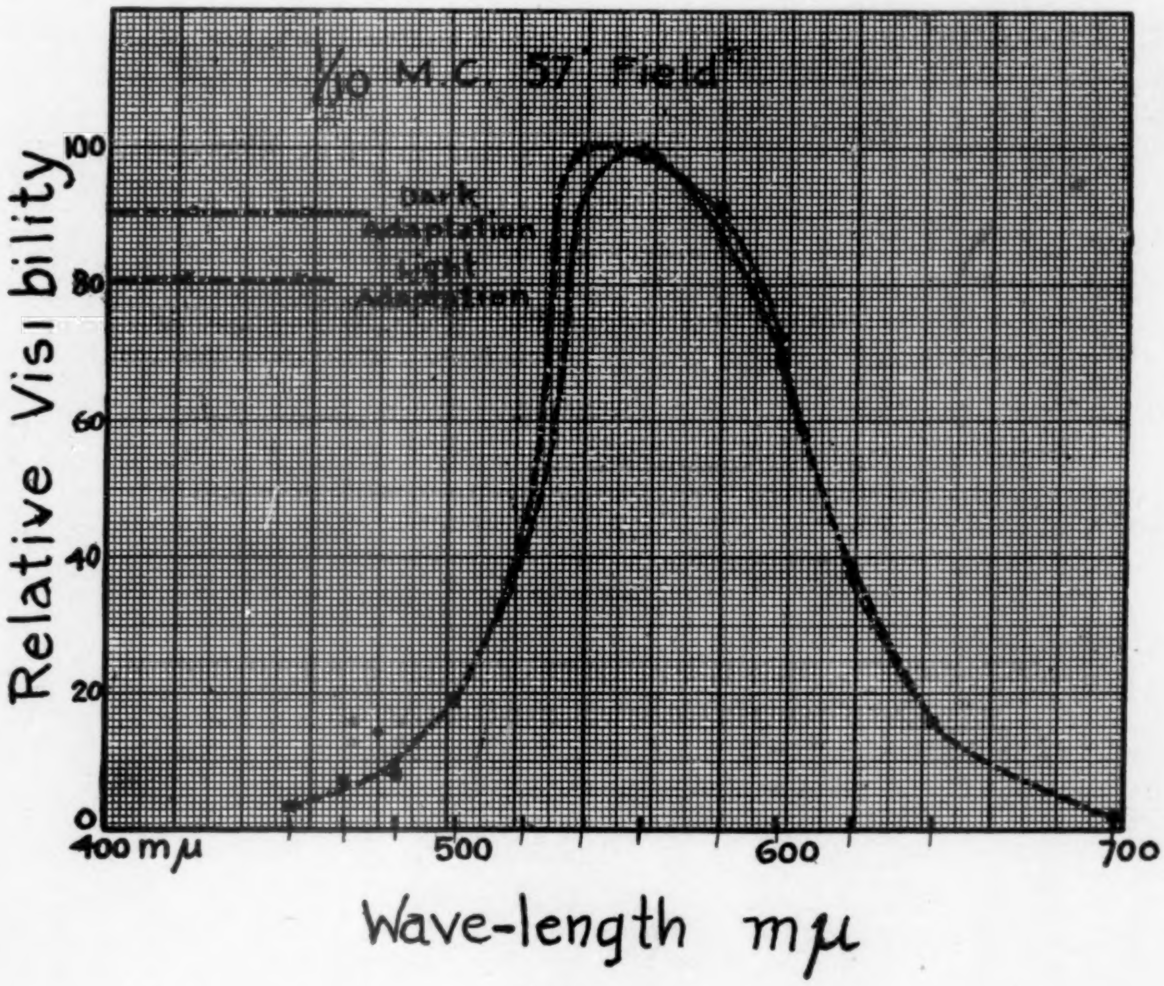


FIG. 22

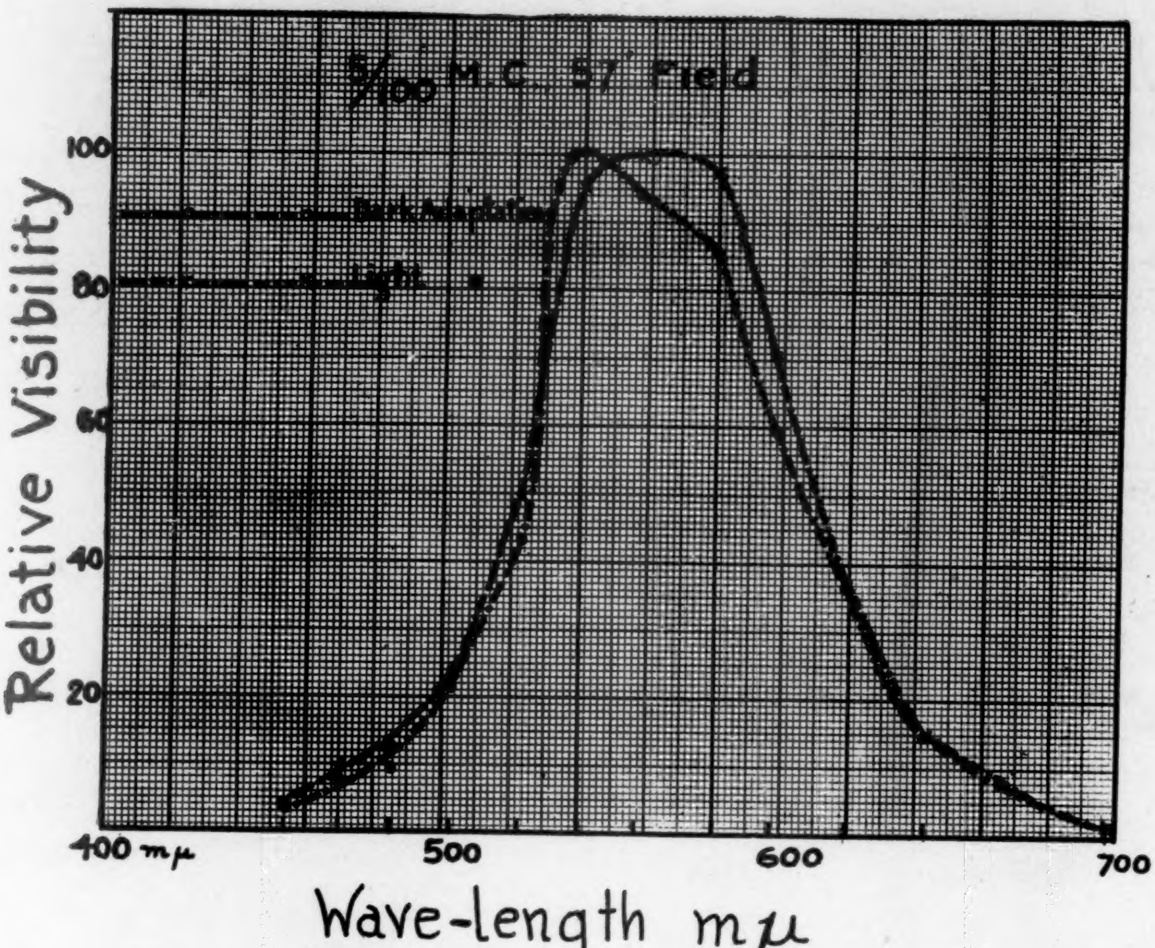

5/100 M.C. 57' Field
Light
Relative Visibility
100
80
60
40
20
400 mμ
500
600
700
Wave-length mμ

FIG. 23

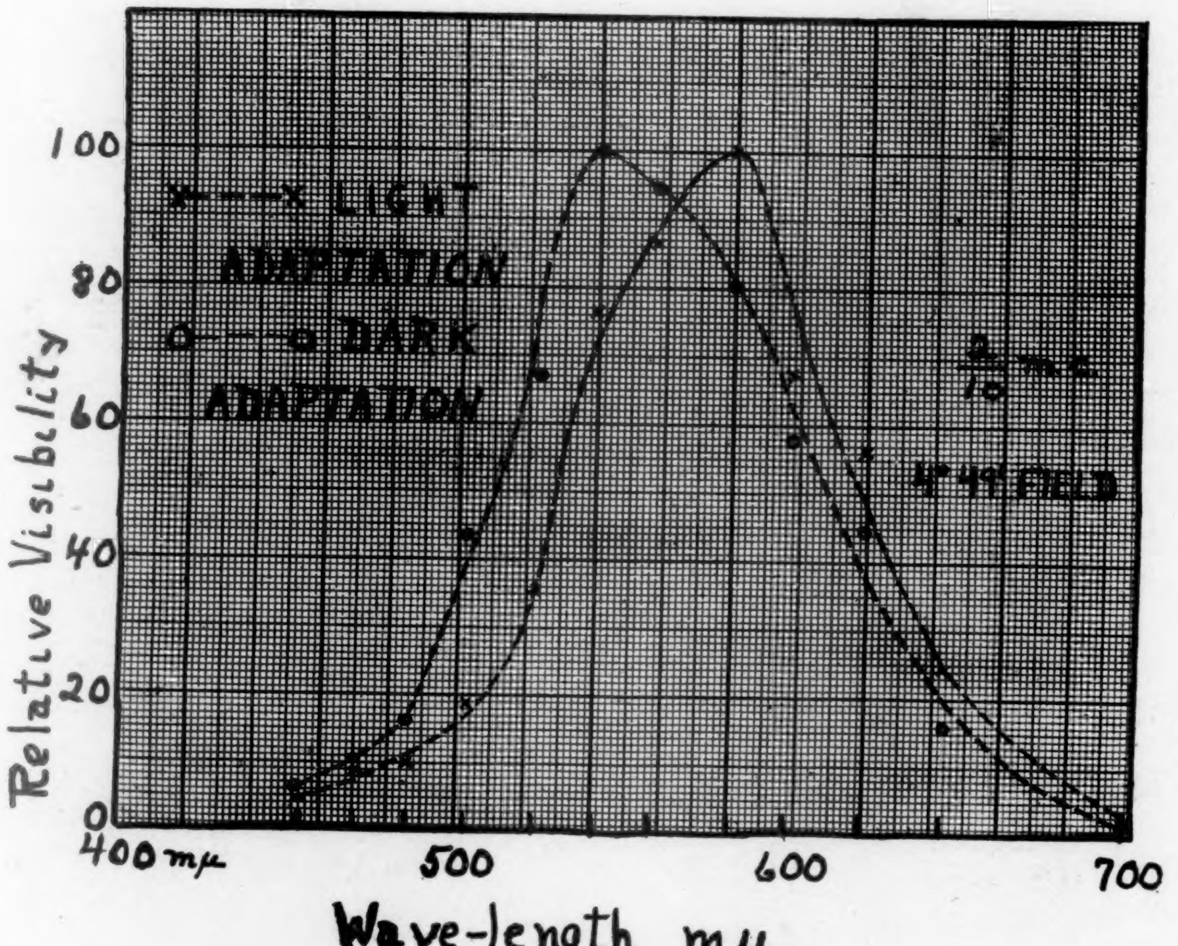
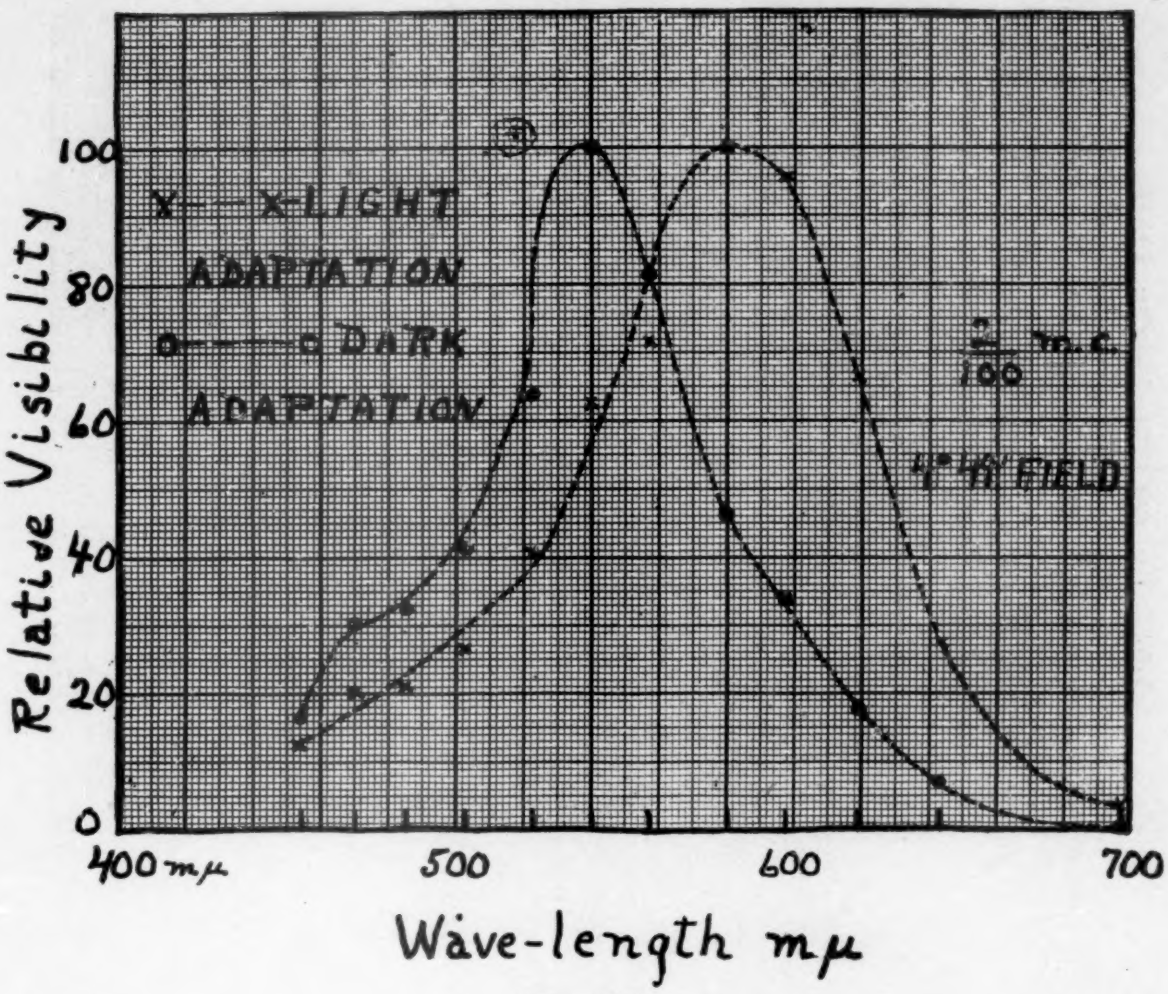
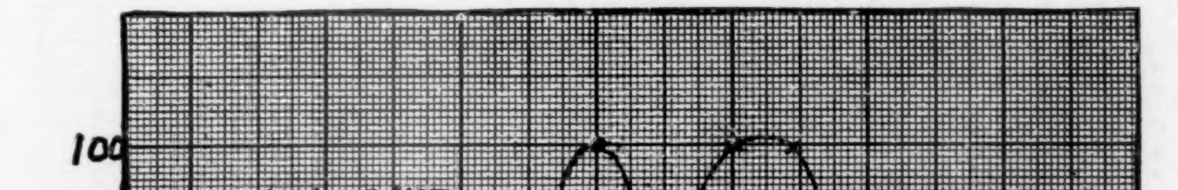

x---x LIGHT ADAPTATION
o---o DARK ADAPTATION
2/10 m.c.
4° 41' FIELD
Relative Visibility
100
80
60
40
20
0
400 mμ
500
600
700
Wave-length mμ

FIG. 24



100
80
60
40
20
0
400 mμ
500
600
700
Relative Visibility
Wave-length mμ
x---x LIGHT
ADAPTATION
o----o DARK
ADAPTATION
$\frac{2}{100}$ m.c.
4° 49' FIELD

FIG. 25



100
80
60
40
20
0
400 mμ
500
600
700
Relative Visibility
Wave-length mμ
x---x LIGHT
ADAPTATION
o---o DARK
ADAPTATION
$\frac{1}{100}$ m.c.
4° 49' FIELD

FIG. 26

when the observer was adapted to an illumination whose horizontal component was approximately the same intensity as the stimulus light, 0.929 f.c. or 10 m.c. instead of 12.5 f.c. as was used for all the work under light adaptation. The results indicate that a visibility curve obtained under such conditions is intermediate in type. That is, when compared with the curve for dark adaptation, the curves for both conditions of light adaptation show an increase in sensitivity to the long wave-lengths, but the increase is less in amount for the lower level of adaptation than for the higher. And (b) determinations at several points in the red were made under conditions of incomplete dark adaptation, *i.e.*, at intervals of from 5 to 30 minutes after the light was excluded from the room. The observer's sensitivity to red as compared with white light was found to decrease gradually as dark adaptation proceeded. We have not, however, attempted a complete investigation of either of these points. The conclusions stated have been drawn tentatively from only a few observations. It is hoped that at some future time further investigations can be made of the effect of different levels and conditions of adaptation on the visibility curve.

One particular aspect of the problem presented by the effect of adaptation, of especial interest in view of its practical application, may be mentioned here. In ordinary photometric work the determinations are usually made in a dark room illuminated only by the standard and comparison lamps. In such cases the observer's state of adaptation will obviously vary with the intensity of the sources of light employed and their distances from the photometer head. In order to ascertain the effect of this factor it would perhaps be of value to determine visibility curves for a wide range of intensities under experimental conditions such that the state of adaptation of the observer's eye corresponded to the intensity level at which the determination was made.

Also it may be noted that in certain standardizing and testing laboratories where continuous service is required of the photometrist for several hours a day, the photometer is boxed in and the comparisons are made in a light room in order to provide

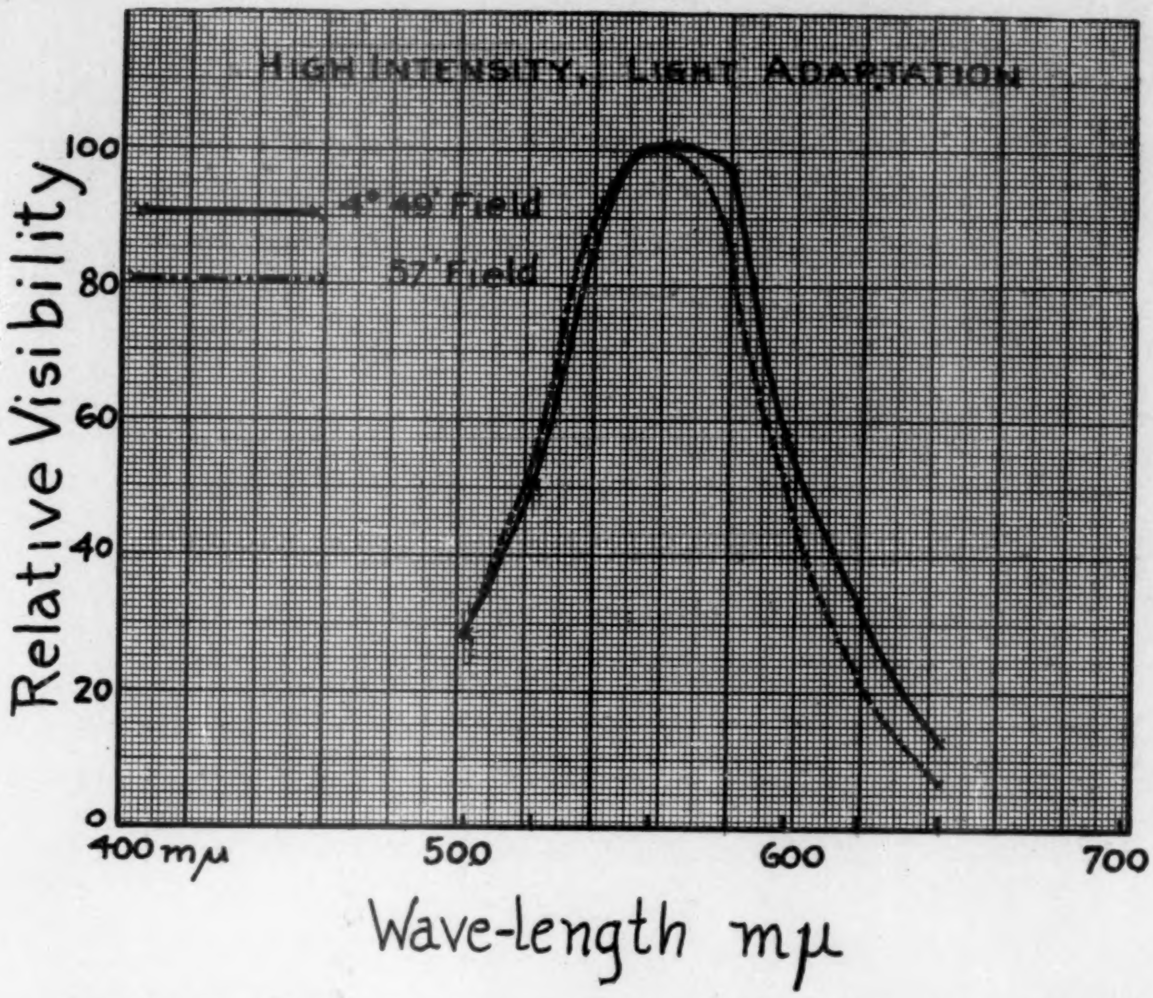
more comfortable conditions of working; *i.e.*, the determinations are made with a light adapted eye. In view of the preceding results showing the effect of state of adaptation on the value of the photometric match obtained, a close agreement could scarcely be expected between the results obtained in these laboratories for lights differing in composition and those obtained in laboratories in which the work is done in a dark room. In short the failure to work under standard conditions with regard to the intensity of illumination of the photometric field, size of field, and state of adaptation of the eye, is doubtless responsible for a great deal of the disagreement in results which is now found to occur from time to time for a given observer and for different observers in the practice of heterochromatic photometry. This disagreement of results which occurs even in case of the comparatively small differences in composition of light found among the commercial illuminants presents, it scarcely need be noted here, one of the most important and perplexing problems yet to be solved in connection with the subject of laboratory and commercial photometry.

C. The Effect of Size of Photometric Field on the Visibility Curve

The data given in Tables XIII-XVI have also been plotted in order to show the effect of size of photometric field on relative visibility. These curves are given in Figs. 27–34.

High and medium intensities, light and dark adaptation. The curves for high and medium intensities for light and dark adaptation are given in Figs. 27–30. For the extrafoveal size of field these curves show a slightly lower sensitivity on the blue and a considerably higher sensitivity on the red side of the curve. That is, the curve for this size of field is broader than that for the foveal size and is shifted slightly towards the red.

Low intensities, light and dark adaptation. The effect of size of field at low is greater than at medium and high intensities. The comparison for the effect of size of field may be made roughly in the large group of curves given in Fig. 8, or more minutely in the selected pairs of curves shown in Figs. 31–34.



FIGS. 27–32. Showing for comparison visibility curves for foveal and extrafoveal sizes of field under each of the following conditions: high intensity, light adaptation; high intensity, dark adaptation; medium intensity, light adaptation; medium intensity, dark adaptation; low intensity (0.2 m.c.), light adaptation; low intensity (0.01 m.c.), dark adaptation.

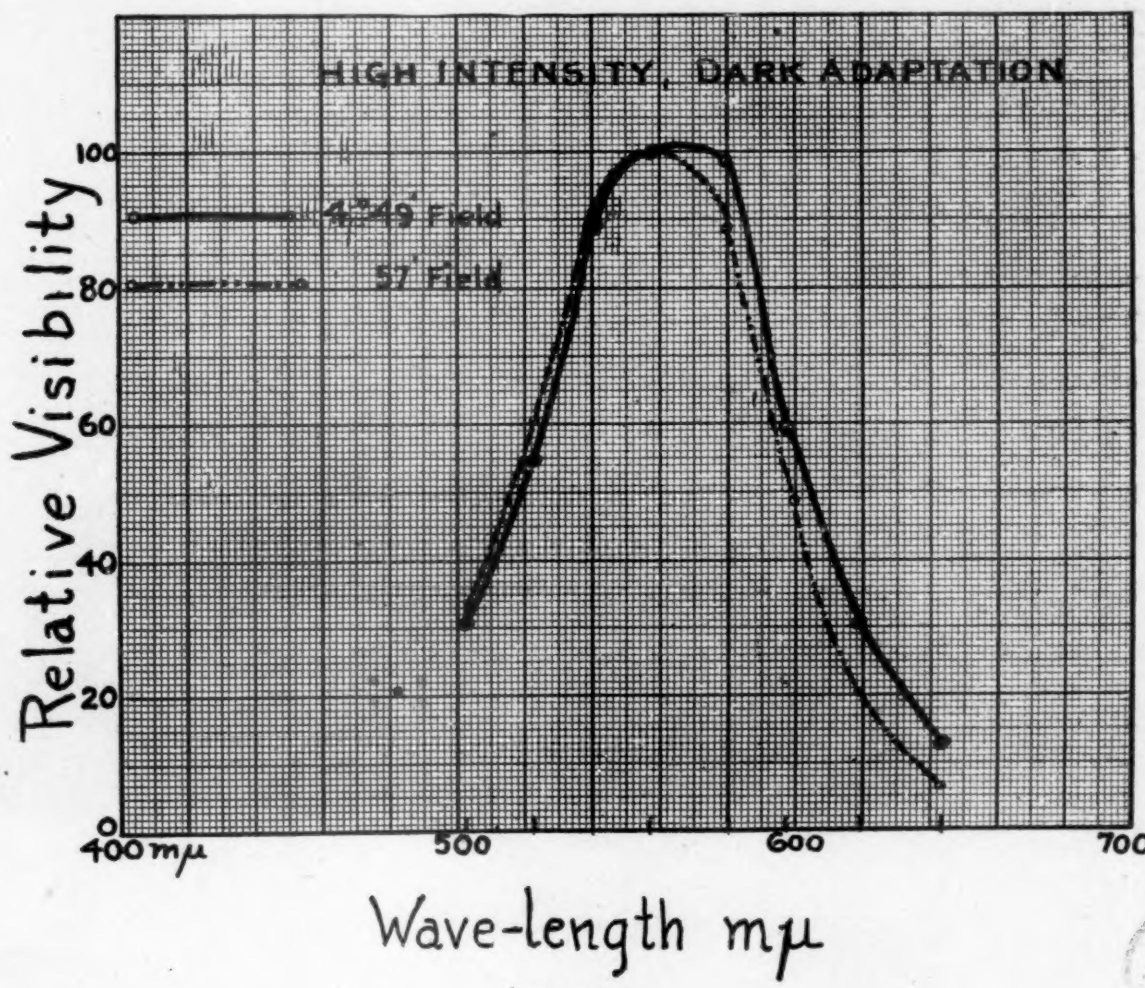


FIG. 28

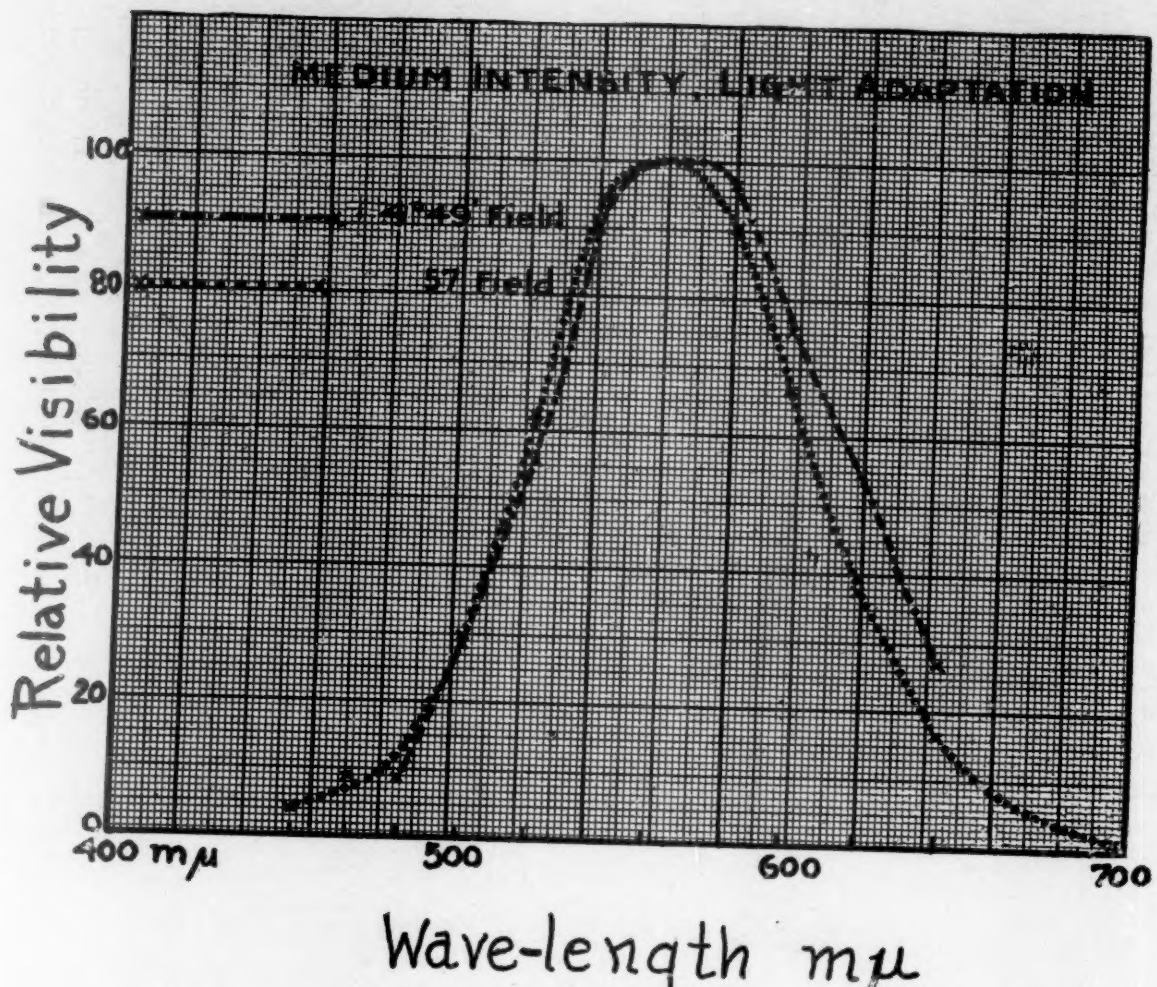

MEDIUM INTENSITY, LIGHT ADAPTATION
Relative Visibility
4°49' Field
57' Field
100
80
60
40
20
0
400 mμ
500
600
700
Wave-length mμ

FIG. 29

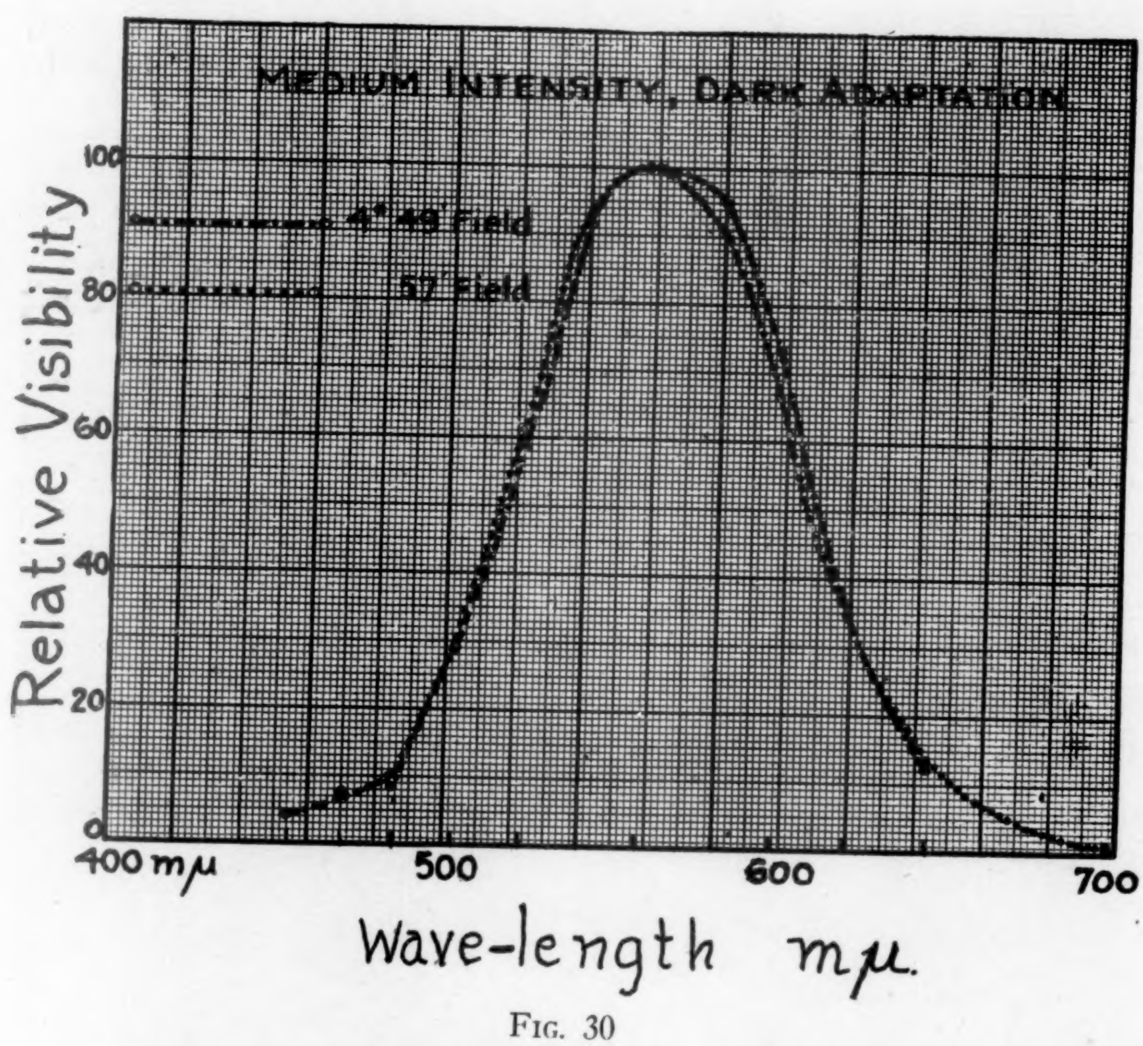
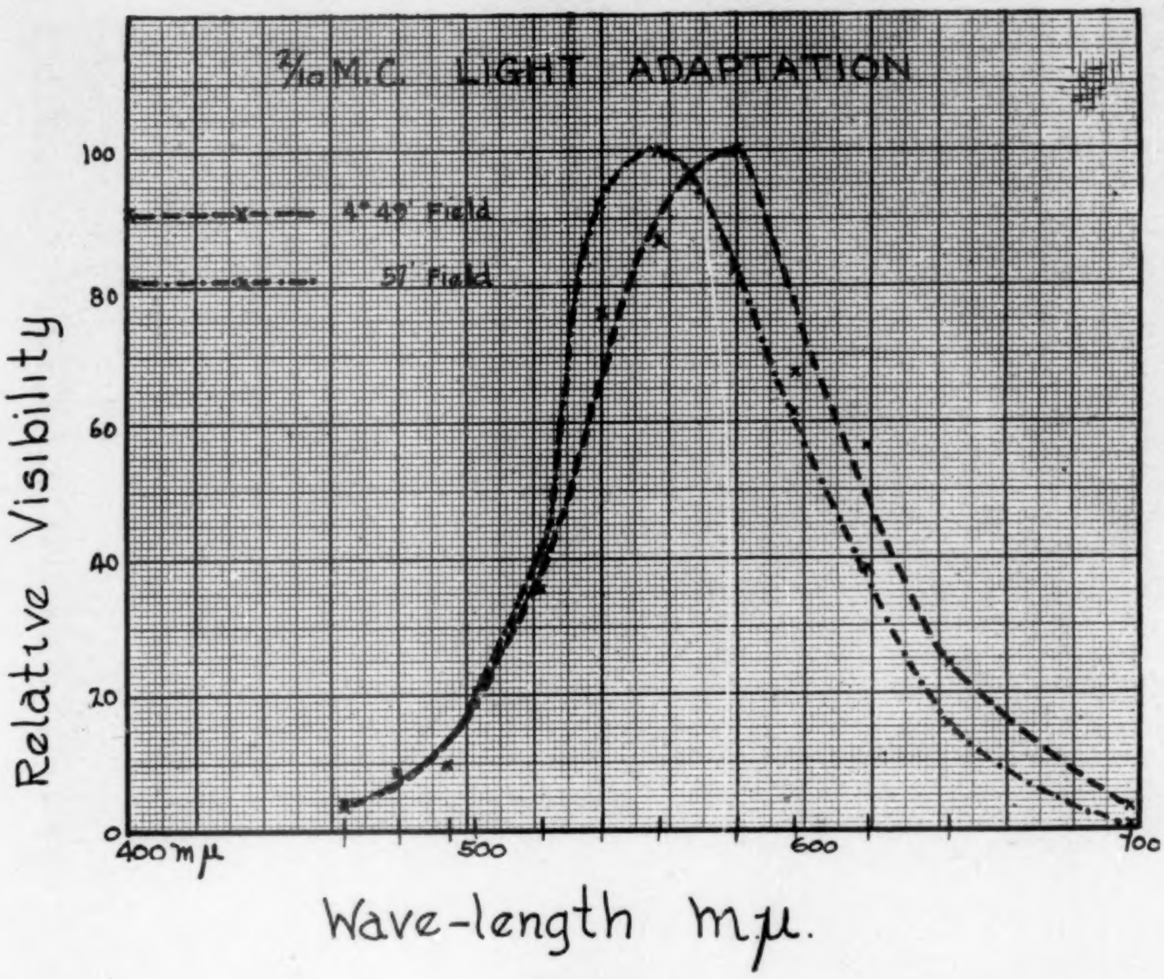
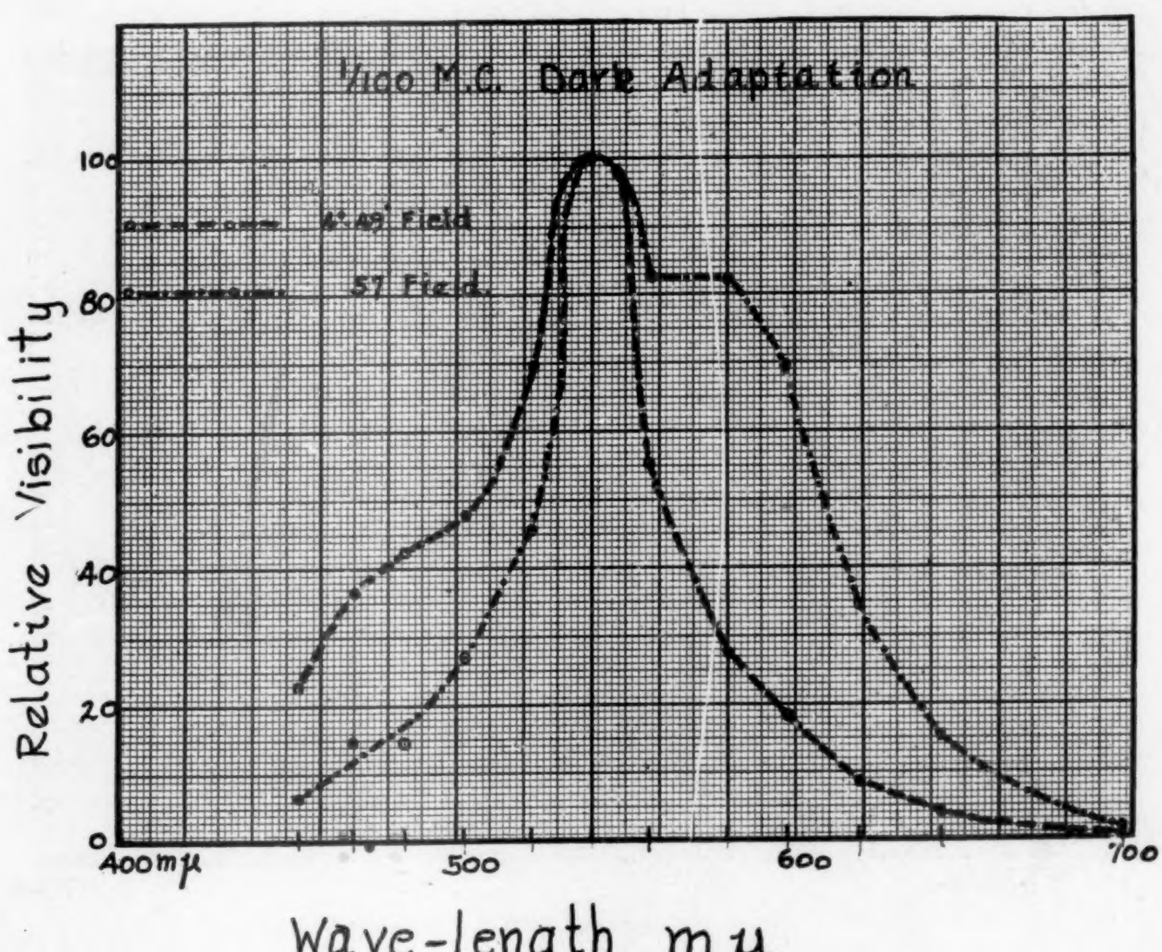

MEDIUM INTENSITY, DARK ADAPTATION
Relative Visibility
4°49' Field
57' Field
100
80
60
40
20
0
400 mμ
500
600
700
Wave-length mμ.

FIG. 30



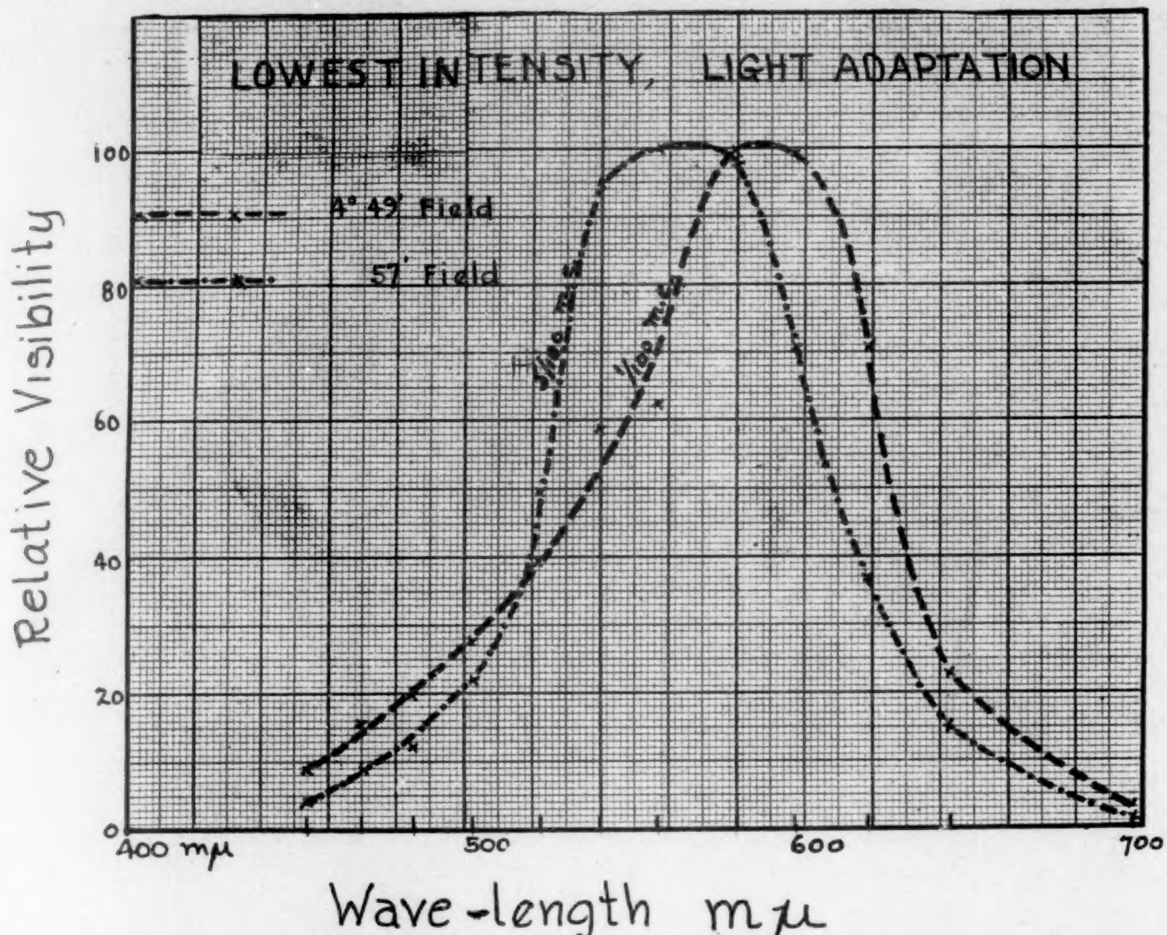
3/10 M.C. LIGHT ADAPTATION
4° 49' Field
57' Field
Relative Visibility
Wave-length mμ.

FIG. 31



1/100 M.C. Dark Adaptation
4° 49' Field
57' Field
Relative Visibility
Wave-length mμ

FIG. 32



FIGS. 33–34. Showing for comparison visibility curves for the lowest intensity (approximately threshold) that could be used under light adaptation with foveal size of field (0.05 m.c.) and with extrafoveal size of field (0.01 m.c.); and under dark adaptation with foveal size of field (0.01 m.c.), and with extrafoveal size of field (0.001 m.c.).

FIG. 34

Since the same intensities could not be used throughout for the extrafoveal and foveal sizes of field, the comparison of the effect of size of field at the same intensity of light can be made at only three of the low intensities, 0.2, 0.02 and 0.01 m.c., for dark adaptation, and at only one, 0.02 m.c., for light adaptation. The use of very low intensities in the determinations for light adaptation was not possible, it will be remembered, because of the comparatively high threshold values which are found under light adaptation. Under dark adaptation the curves for the foveal size of field show at each intensity for which the comparison can be made, a lower sensitivity to the short and a higher sensitivity to the long wave-lengths than the corresponding curves for the extrafoveal size of field. At the intensities of 0.02 and 0.01 m.c. the difference in the two cases is very marked. The curves for 0.01 m.c. are plotted in Fig. 31. The curves for light adaptation at 0.2 m.c. are shown in Fig. 32. These curves show that the effect of size of field under light adaptation is the reverse of that found under dark adaptation. That is, under light adaptation the curve for the foveal size of field shows a lower sensitivity to the long wave-lengths and a higher sensitivity to the short wave-lengths than the curve for the extrafoveal size.

It may be of interest, too, to make the comparison for the effect of size of field at the lowest intensities (approximately threshold), which were used, for each condition employed. Under dark adaptation these intensities are respectively 0.01 and 0.001 m.c. for foveal and extrafoveal sizes of field; under light adaptation they are 0.05 and 0.01 m.c. The curves for these intensities, grouped to permit of a comparison of the effect of size of field at the same state of adaptation, are given in Figs. 33–34. As before, it is seen that the effect under light adaptation is the reverse of that found under dark adaptation. In the former case, the curve for the extrafoveal size of field is shifted toward the long wave-length end of the spectrum; in the latter, towards the short wave-length end, as compared with the corresponding curves for the foveal size of field. This effect is quite pronounced.

Obviously in this study of the effect of the three factors,

intensity of light, state of adaptation of the eye, and size of the photometric field on the visibility curve, any or all of the following possibilities were presented: the effect of varying any one of the factors while the other two were held constant; the effect of varying two while the third was held constant; and the effect of varying all of them simultaneously. Thus far in the discussion of the results the first of these possibilities has in general been followed. As was seen in the historical section, however, considerable attention has been given to one case of the second of these possibilities by previous investigators, namely, the effect of change of intensity for foveal and extrafoveal sizes of field. It will be recalled from this previous discussion that earlier investigators have failed to agree as to the occurrence of selectiveness to intensity for small sizes of field. For example, Hering, Sherman, and Koster found a slight Purkinje effect for foveal sizes of field; Dow and Ives, the reverse of this effect; while von Kries and Troland deny any change in the fovea's selectiveness of sensitivity to wave-length with change of intensity. These conflicting results may have been due, as we have already shown, in some cases to differences in the size of field used and in others to inadequate provisions for the control of fixation. From our own data, however, it is seen that such disagreement is to be expected from the limited extent of these investigations. That is, the effect on relative sensitivity for foveal stimulation depends upon the wave-lengths and the intensities compared and also on the state of adaptation of the eye. Consequently no general conclusions should have been drawn from these investigations in which determinations were made in most cases at only two points in the spectrum, at only two intensities of light, and for only one state of adaptation of the eye.

In order to demonstrate the statement made above, *i.e.,* that the effect on relative sensitivity for foveal stimulation depends upon the wave-lengths and intensities compared and on the state of adaptation of the eye, some typical data from our results have been assembled in Table XVIII. These data show the reduction of energy expressed in ratios required in different parts of the spec-

trum to reduce the photometric value by an equal amount from a given initial value. From this table it is seen, for example, that with an initial intensity of 75 m.c. the ratio of reduction for both light and dark adaptation, foveal size of field, is in every case smaller for the long than for the short wave-lengths; that

TABLE XVIII

Showing the ratios of decrease of energy required in different parts of the spectrum to produce selected reductions in photometric value. A high value of ratio indicates that a relatively small decrease in energy is needed to produce the selected reduction, or that there is a relatively rapid darkening of the color with decrease of energy.

	Light Adaptation, Size of Field, 57 min.		Dark Adaptation, Size of Field, 57 min.		
Wave-length	75 to 0.05 m.c.	5 to 0.05 m.c.	75 to 0.01 m.c.	10 to 0.01 m.c.	5 to 0.01 m.c.
454 mμ		.0158			.00148
470		.0132		.000537	.00138
485		.0107		.000631	.00148
502.5	.00151	.0229	.000229	.00145	.00288
522.5	.00115	.0191	.000219	.00178	.0038
597.5	.000742	.0132	.000126	.000912	.00229
619	.000646	.0166	.00011	.000741	.00251
643	.000490	.0155	.0000776	.000537	.00245
697		.00794		.000389	.001585

is, the results show the reverse of the Purkinje effect. In reducing the intensity from 10 to 0.01 m.c. for dark adaptation, however, the Purkinje effect is shown when the result at 470 mμ is compared with that at 597.5; the reverse of this effect when the comparison is made at 597.5 and 619 mμ; and no change in relative sensitivity is found when the comparison is made at 470 and 643 mμ. Similarly for light adaptation, in reducing the intensity from 5 to 0.05 m.c., the Purkinje effect is shown when the result at 485 is compared with that at 619 mμ; the reverse of this effect when 454 is compared with 697 mμ; and no change in relative sensitivity is found when the result at 470 is compared with that at 597.5 mμ. It is obvious then that photometric data obtained for a single pair of wave-lengths or for two or only a limited number of intensities are inadequate to demonstrate whether or not the Purkinje phenomenon occurs with foveal sizes of field.

For further evidence on this point and for a comparison of the magnitude of the Purkinje effect for foveal and extrafoveal

sizes of field, reference may be made again to the curves shown in Figs. 9–12. These charts show the visibility curves for the highest and lowest intensities investigated under the four conditions: light adaptation, foveal size of field; dark adaptation, foveal size of field; light adaptation, extrafoveal size of field; and dark adaptation, extrafoveal size of field. From these curves it is seen that the selective effect of intensity is most pronounced with dark adaptation, extrafoveal size of field; next with light adaptation, extrafoveal size of field; then with dark adaptation, foveal size of field; and least with light adaptation, foveal size of field. In the last two cases the effect is slight as compared with the first two, that is, for the foveal as compared with the extrafoveal size of field; however, the effect is significant for both types of adaptation, although, as has already been pointed out, it is in general the reverse under light adaptation of what it is under dark adaptation.

V. SUMMARY AND CONCLUSIONS

The so-called visibility function represents one of the most widely investigated and, from both practical and theoretical points of view, one of the most important of the psychophysical functions. Heretofore a number of determinations have been made of the average visibility curve for a large group of normal observers. The present study was undertaken in the belief that further investigation of the effect of various experimental conditions was necessary before such average visibility curves could be determined under properly controlled conditions.

Among the factors which influence the results of determinations of relative visibility may be mentioned: the photometric method employed, the intensity of stimulus, the size of the photometric field, the state of adaptation of the observer's eyes, and the length of exposure of the photometric field. In the present study an investigation has been made of the effect on the visibility curve of three of these factors, namely, intensity of light, size of photometric field, and state of adaptation of the eye. Curves were determined at from nine to twelve intensities ranging from 75 m.c. to values near the threshold. At each intensity determinations were made for a foveal and an extrafoveal size of field and for light and dark adaptation. In the work in the light room an adaptation period of fifteen minutes was found to be sufficient for general brightness adaptation. For work in the dark room a period of thirty minutes was allowed. The equality of brightness method was used in making the photometric determinations. The photometric field was exposed for a constant interval of time, namely, two seconds. The spectrum lights used as stimuli were freed from impurities by the use of filters especially selected for this purpose. The energies of these stimuli were measured directly at the analyzing slit by means of a bismuth-silver thermopile and a special Thompson galvanometer.

From the results of the experiments carried out under the above conditions the following conclusions may be drawn:

1. The effect of intensity of light on the visibility curve.

(a) The visibility curve is found to change in shape with change of intensity throughout the range investigated; namely, from 75 m.c. to an intensity near the threshold.

(b) Changes in the position of the point of maximum visibility with change of intensity are found only for intensities below 0.2 m.c. For curves determined at intensities above this level, the point of maximum visibility remains at or near 557 mμ.

(c) Between 75 and 1 or 2 m.c. decrease of intensity causes a broadening of the visibility curve which is greater on the long than on the short wave-length side of the maximum. For this range of intensities, therefore, the results show the reverse of the Purkinje effect.

(d) Very marked changes in the shape and position of the curve occur when the intensity level at which the determinations are made is decreased from 1 or 2 m.c. to still lower values. The magnitude and direction of the changes vary with the state of adaptation of the observer's eye, and with the size of the photometric field. Investigations made for two sizes of field and for conditions of light and dark adaptation gave the following results:

(i) Dark Adaptation, Size of Field 4 deg. 49 min.: With decrease of intensity the visibility curve becomes very asymmetrical in shape. The maximum of the curve shifts toward the blue wave-length end of the spectrum; at an intensity of 0.002 m.c. the point of maximum visibility is in the neighborhood of 500 mμ and the curve is once more approximately symmetrical.

(ii) Light Adaptation, Size of Field 4 deg. 49 min.: With decrease of intensity the curve changes somewhat in shape and the point of maximum visibility shifts toward the long wave-length end of the spectrum. For an intensity of 0.01 m.c. the maximum is near 580 mμ. Thus the results again show the reverse of the Purkinje effect.

(iii) Dark Adaptation, Size of Field 57 min.: The curve changes in shape with decrease of intensity. The region of maximum visibility shifts to 540 mμ approximately.

(iv) Light Adaptation, Size of Field 57 min.: Under these conditions minor changes in shape are found to occur, but no change in the position of the maximum is detected.

2. The effect of the state of adaptation of the observer's eye on the visibility curve.

(a) If the visibility curves for the same intensity and size of field are compared, a change from light to dark adaptation is found in every case to result in the typical Purkinje effect. This may be due to an increase in the ordinates on the short wave-length side of the curve; a decrease in those on the long wave-length side of the curve; or a combination of both of these effects. The effect produced, however, varies in magnitude with the level of intensity and size of field employed.

(b) The change in the visibility curve with change of state of adaptation is slight at high intensities.

(c) The effect is also slight at medium intensities, if a foveal size of field is used.

(d) It is considerable, however, at medium intensities when a size of field of 4 deg. 49 min. is used.

(e) The change is of very great magnitude at low intensities. This is true both for foveal and extrafoveal sizes of field, although the effect is greatest for the latter.

3. The effect of the size of the photometric field on the visibility curve.

(a) Visibility curves determined at the same level of intensity and under the same conditions of adaptation are found to differ in shape when determined with foveal and extrafoveal sizes of stimulus field. For the two sizes of field used, namely, 4 deg. 49 min. and 57 min., the following results are found:

(i) At high and medium intensities for both light and dark adaptation, decrease of size of field results in a decrease in sensitivity to the long and an increase in sensitivity to the short wave-lengths.

(ii) At low intensities the effect of size of field is of greater magnitude than that found at high and medium intensities. The direction of the change depends upon the state of adaptation. Under light adaptation the effect is similar to that found at high

and medium intensities; *i.e.,* there is a decrease in sensitivity to the long and an increase in sensitivity to the short wave-lengths with decrease in size of field. Under dark adaptation there is an *increase* in sensitivity to the long and a *decrease* in sensitivity to the short wave-lengths with decrease in size of field.

(b) A change in the shape of the visibility curve as a result of decrease of intensity of light or change in state of adaptation of the eye is found to occur with both foveal and extrafoveal sizes of field. The changes are greater, however, in the latter than in the former case.

(c) It is not possible to determine whether the Purkinje phenomenon occurs in the fovea from investigations made at only a limited number of intensities and a limited number of points in the spectrum. These limitations rather than differences in adequacy of control of fixation have doubtless been the chief cause of disagreement in the results obtained by previous investigators.

(d) No experimental condition has been found in this study under which the eye is entirely free from the selectiveness of response to intensity. The nearest approach to it is obtained under light adaptation with foveal size of field at high intensities.

In addition, the following general conclusion may be drawn from the results of this and other studies conducted in this laboratory: The results obtained by any given observer in heterochromatic photometry are subject to the influence of the following variables: wave-length of light, intensity of light, length of exposure of the eye, state of adaptation of the eye, and size of the photometric field. The effect of any or all of these factors may differ from observer to observer. Although it is difficult to make the judgment of equality of brightness in the presence of difference in hue, as is required in heterochromatic photometry by the equality of brightness method, a great deal of improvement could be made in the use of that method if due regard were paid to the influence of these factors.

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